AN INVESTIGATION OF CERTAIN PROBLEMS RELATED TO THE CLASSIFICATION AND PHYSICAL PROPERTIES OF FAINT BLUE STARS

Alexander Brown

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AN INVESTIGATION OF CERTAIN PROBLEMS RELATED TO THE CLASSIFICATION AND PHYSICAL PROPERTIES OF FAINT BLUE STARS

by

ALEXANDER BROWN

A dissertation submitted for the degree of Doctor of Philosophy at the University of St. Andrews.

September 1978

CERTIFICATE

I certify that Alexander Brown has spent nine terms in research work at the University Observatory, St. Andrews, that he has fulfilled the conditions of Ordinance General No. 12 and Senate Regulations under Resolution of the University Court, 1967, No. 1, and that he is qualified to submit the accompanying dissertation in application for the degree of Ph.D.

DECLARATION

Except where reference is made to the work of others, the research described in this thesis and the composition of the thesis are my own work. No part of the work has been submitted for either professional qualifications or another degree at this or any other university.

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ERRATA

Page 2, Table 1.1,	for 'Luyten (1955 - 1969)' read 'Luyten (1958 - 1969)'.
	for 'Palomer' read 'Palomar'.
Page 4, line 12,	for 'equalibrium' read 'equilibrium'.
Page 5, line 11,	for 'skys' read 'skies'.
Page 9, line 7,	for '0.05' read '0.005'.
line 12,	for '0.01' read '0.001'.
Page 12, line 12,	for 'andode' read 'anode'.
Page 13, line 3,	after ' ... intermediate passbands.' include 'More recently the use of interference filters has become popular.'.
Page 18, line 2,	for 'Shobbrock' read 'Shobbrook'.
Page 22, line 6,	for 'numbers' read 'magnitudes'.
line 10,	for 'stop' read 'step'.
Page 53, Table 4.4,	for 'CD' read 'CPD'.
Page 55, Table 4.4,	for 'CD' read 'CoD'.
Page 61, line 26,	for 'dependent' read 'independent'.
Page 81, line 16,	for 'alternate name' read 'alternative names'.
Page 95, line 19,	for 'conservative error' read 'conservative estimate'.
Page 118, line 14,	for 'encoutered' read 'encountered'.
Throughout Chapter 7	for 'Shobbrock' read 'Shobbrook'.
Page 136, line 24,	for 'Θ(DS) + 0.12' read 'Θ(DS) + 0.012'.
Page 150, line 11,	for 'Likelyhood' read 'likelihood'.
Page 174, line 12,	for 'Baum, W.A., 1972.' read 'Baum, W.A., 1962.'.

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ABSTRACT

Faint blue stars situated out of the galactic plane have been studied using a variety of techniques. Strömgren photometry has been obtained for a number of these stars and classifications derived from the photometry. An interference filter centred at 3775 A near the Balmer discontinuity has been used in conjunction with the Strömgren filters. Observation of Strömgren standard stars, bright B stars and faint blue stars have been used to study the behaviour of the colours (u-38) and (38-b). Reddening-free parameters [u-38] and [38-b] have been evaluated and [38-b] is found to be linearly related to the Crawford Hβ index for B-type dwarfs, giants and supergiants. This relationship has been used to derive absolute magnitudes and distances for faint apparently normal B stars. [38-b] allows this work to be done at fainter magnitudes than possible with Hβ photometry.

A filter pair centred on the HeII λ4686 line has been used to study O-type stars including O subdwarfs. The resulting index is strongly correlated with the equivalent width of the HeII line and has a range of $0^{m}.13$. It is possible to separate sdO, O and Of stars using this index. Although the index is correlated with absolute magnitude for O and Of stars, the detailed behaviour precludes the accurate determination of absolute magnitude for dwarfs and giants. Theoretical indices have been computed from the models of Kudritzki and agree well with the results for stars with high helium abundance. These computations suggest that it is

possible to separate sdO and DO stars with this system. The results have also been compared with the work of Auer and Mihalas.

30 A/mm image tube spectra have been used for Balmer line width measurement and radial velocity determination. The line widths were used to estimate surface gravities for faint blue stars in conjunction with temperatures determined from the Strömgren [u-b] index. The results indicate that 30 A/mm image tube spectra can be used successfully for surface gravity determination. 75 A/mm image tube spectra have been used for spectral classification as a check on the classification provided by Strömgren photometry.

The kinematics of certain subdwarfs and main sequence stars at high galactic latitude have been considered. Proper motions have been employed as a check for subluminosity using appropriate absolute magnitudes. Galactic orbits have been computed using the Schmidt model of the galactic force field. Several B-type dwarfs and subdwarfs were found to have been ejected from the galactic plane at high velocity. Thirty percent of the stars previously classified as normal dwarfs were found to be subluminous. The evolutionary implications of these results are discussed.

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CHAPTER 1

INTRODUCTION AND HISTORICAL BACKGROUND

Humason and Zwicky (1947) discovered a substantial number of faint blue stars during a search for white dwarfs in the Hyades and the region of the North Galactic Pole (NGP). Many of these stars were clearly not white dwarfs but if they were normal main-sequence stars, they were situated well out of the galactic plane and far from the normal star-formation regions. Humason and Zwicky concluded that the stars were similar to the blue horizontal branch stars seen in globular clusters. Many surveys followed this discovery using a variety of techniques and the more important ones are listed in Table 1.1 with the regions covered and techniques used.

The faint blue stars were found to be a very varied group containing many interesting highly-evolved objects. Under the global title of 'faint blue star' are found:-

i) subdwarf O stars (sdO) which have higher surface gravities and hence broader lines than main-sequence O stars. They show the HeII λ4686 line strongly in absorption.

ii) subdwarf B stars (sdB) which have colours similar to normal B stars but have higher surface gravities and hence broader Balmer lines. These stars often show weaker HeI lines than main-sequence stars.

iii) subdwarf F and G stars (sdFG) which also have higher surface gravity than their main-sequence counterparts and are often highly metal deficient.

Table 1.1 Major Faint Blue Star Surveys

	Abbreviation	Area	Method
Humason and Zwicky (1947)	HZ	NGP + Hyades	Four-Colour Photography
Luyten (1955 - 1969)	LB	Most regions out of the galactic plane	Proper Motions
Iriate and Chavira (1957)	TN	NGP	
Chavira (1958,1959)	TS,TN	SGP,NGP	Multicolour Photography
Haro and Luyten (1962)	PHL	SGP	
Feige (1958)	F	NGP + SGP	Red and Blue Palomer Schmidt plates
Cowley (1958)	-	NGP + SGP	Schmidt Objective-Prism Plates
Slettebak and Stock (1959)	-	NGP	Schmidt Objective-Prism Plates
Slettebak and Brundage (1971)	SB	SGP	
Greenstein (1966) and Greenstein and Sargent (1974)	FB	Mainly Northern Stars	Spectroscopy
Sargent and Searle (1968)	-	Feige Stars	Spectroscopy
Jaidee and Lyngå (1969)	JL	SGP	2-Colour Schmidt Plates
Graham (1970)	-	Feige Stars	Strömgren Photometry
Newell (1973)	-	Mainly Southern Stars	Photometry and Spectroscopy

iv) white dwarfs (DA, DB, DO and DC) which have very high surface gravities and, if they show any lines, the lines are very broad.

v) horizontal branch stars (HB or hb) which are the counterparts of the Population II horizontal branch stars found in globular clusters (see for instance Newell (1970)). These stars have lower surface gravities than dwarfs of similar colour and are often identified by the large size of their Balmer discontinuities.

vi) Many apparently normal B, A and F stars are also found in the galactic halo and frequently no peculiarities can be detected in these stars using photometry or low dispersion spectroscopy. However many such stars when studied with high dispersion spectra reveal abundance peculiarities. A number of these stars have large space motions. This group of stars contains both Population I and Population II stars.

The relative proportions of each type of star changes as fainter apparent magnitudes are considered with main-sequence stars giving way to subdwarfs which are in turn outnumbered by white dwarfs at sufficiently faint magnitudes. Clearly this group which contains many stars in advanced stages of evolution is important for the study of both stellar and galactic evolution.

Spectroscopic criteria for the classification of faint blue stars were proposed by Sargent and Searle (1968) and since then these have formed the basis of most classification work. Newell (1973) and Greenstein and Sargent (1974) have developed techniques for the determination of atmospheric parameters using photometry and intermediate-dispersion spectra. Both authors applied their techniques to a sample of faint blue stars. The relationship between the faint blue stars and the globular cluster horizontal branch stars was further confirmed by Newell's discovery of gaps in the log g - log T_{eff} distribution of his stars which were also present in the distribution of globular cluster stars. Newell and Graham (1976) have strengthened this finding by the inclusion of further data.

The understanding of the evolutionary state of faint blue stars has been aided by the advances in stellar atmosphere modelling which have allowed the easy construction of models in LTE (local thermodynamic equalibrium) for B stars, including sdB stars (See Baschek and Norris (1970) and Baschek, Sargent and Searle (1972)). More recently, NLTE models for sdO stars have been calculated by Kudritzki (1976) and this has resulted in the first NLTE analysis of an sdO, HD 49798, by Kudritzki and Simon (1978).

A research project at St. Andrews had been initiated by Drs. D. Kilkenny and P.W. Hill to study a large sample of faint blue stars with published proper motions. The project was confined to stars brighter than $14\overset{m}{.}0$ and its aim was to classify the stars using Strömgren photometry. A programme of spectroscopy was also planned to study interesting objects discovered photometrically.

The research reported in this thesis forms part of this larger investigation. Some Strömgren photometry has been obtained but a major portion of the work is concerned with the examination of two additional filter systems which supplement the Strömgren photometry. One of these systems is, in fact, only an extension of the Strömgren system while the other involves the use of a pair of filters centred on the HeII $\lambda 4686$ line. The programme of spectroscopy was also started and, although only a relatively small number of spectra have as yet been obtained, the quality of the information which may be derived from them is discussed.

This research has involved extensive observing at the South African Astronomical Observatory (S.A.A.O.) outstation situated near Sutherland in Cape Province. This site is at a height of just under 2000m. and provides a slightly better than average continental-interior observatory with very dark skys. Observations were also made at the Royal Greenwich Observatory (R.G.O.).

CHAPTER 2

PHOTOELECTRIC PHOTOMETRY - AN OVERVIEW

2.1 Introduction

The emergent radiation from a star carries detailed information about that star in the form of continuum radiation and superimposed spectral lines. These features are primarily governed by the temperatures and pressures found in the outer layers of the star and the chemical composition of the stellar atmosphere. In addition such effects as mass motions in the atmosphere and stellar rotation affect the shape of the spectral lines.

It is the aim of photoelectric photometry to evaluate the properties of the stellar atmosphere from measurements through optical filters of portions of the stellar spectrum. By using a number of filters it is hoped that parameters may be defined which are related to the basic properties of the star. For practical reasons the number of filters must be as small as possible and, since it is difficult for one filter set to be useful for all types of star, filter systems have developed for specific problems and types of star. The first widely used photoelectric system was the UBV system (Johnson and Morgan, 1953) which employed three wide-band glass filters and was used for all types of star. Although the information provided was coarse, it allowed great progress to be made and has been an important factor in the development of stellar astronomy in the last twenty five years. When it became clear that the UBV system was limiting and finer detail could be obtained using more specialised filter sets, new systems employing intermediate bandpass filters were introduced. Examples are the Strömgren uvby system (Strömgren, 1966), which was created for the study of A, F and G stars, and the DDO system (McClure and Van den Bergh, 1968) for late-type stars.

In the following pages the processes involved in the passage of radiation from star to telescope and its conversion to a form convenient to interpretation are discussed.

2.2 Interstellar Reddening

Light passing through space is constantly modified by the gas and dust of the interstellar medium. The primary effect is reddening, which results in light of shorter wavelength being depleted preferentially. Reddening is due to scattering by the interstellar dust grains (Wickramasinghe, Kahn and Metzger (1972) give a general description.). Since it is the form of the unreddened radiation which is sought from photoelectric photometry, an understanding of interstellar reddening is important. This is especially true for early type stars which are sufficiently luminous to be seen at large distances and are often heavily reddened. Fortunately in the case of faint blue stars reddening is less important, especially if studies are made in the direction of the galactic poles, where the amount of interstellar matter is less than that in the galactic plane. Also due to their lower luminosities, faint blue stars are closer than main-sequence stars of the same apparent magnitude. This fact may be used to check if a star is subluminous. A distant star of normal luminosity would show an appreciable reddening whereas a subluminous star, while appearing normal, would be closer and not show the expected reddening. At the galactic poles this fact is not so useful since the interstellar dust is confined to the galactic disc.

The effect of reddening on photometric parameters and diagrams has been investigated through studies of reddened and unreddened early type stars (for instance see Johnson (1965) and Crawford (1975)). When these effects are understood, the amount of reddening between the star and observer may be estimated provided the unreddened star lies near the intrinsic colour line and is not evolved.

A second effect of the interstellar medium is the presence of interstellar absorption lines due to the absorption of stellar photons by atoms in the interstellar gas. The main examples seen at optical wavelengths are the H and K lines of CaII and the D lines of NaI. However in the ultraviolet many interstellar lines, such as Lyman α and lines of CI, CII, SII, SiII and OI, are found.

2.3 Atmospheric Extinction

In general, photometric systems are defined with regard to the light as it was outside the Earth's atmosphere and the effect of the atmosphere on the recorded signal must be removed. The effect of atmospheric extinction is increasingly to absorb and scatter light as the distance the light travels through the atmosphere becomes greater. Thus a star at the zenith is least affected by atmospheric extinction.

The relation between the stellar energy distribution outside the atmosphere, $E(\lambda)$, and the observed distribution, $E'(\lambda,z)$, is

$$E'(\lambda,z) = E(\lambda)\, e^{-K(\lambda)X}$$

where $K(\lambda)$ is the extinction coefficient and X is the air mass at zenith distance z. The air mass, X, may be approximated by sec z, which is correct to within 0.05 for $z \leq 60^\circ$. A more accurate expression (Golay, 1974), used in the reduction of all the photometry discussed later, is

$$X = \sec z - 0.0018167(\sec z - 1) - 0.002875(\sec z - 1)^2 - 0.0008083(\sec z - 1)^3$$

which is accurate to within 0.01 for $X < 10$.

The signal from a star at zenith distance z, $m'(\lambda,z)$, measured through a filter with mean wavelength, λ, is related to the signal outside the atmosphere, $m(\lambda)$, by Bouguer's Law which is

$$m'(\lambda,z) = m(\lambda) + a(\lambda)X \ .$$

This equation only strictly holds for monochromatic radiation of wavelength λ and in fact depends on the type of star observed. In order to overcome this fact, photometric systems are defined by a number of standard stars which have a wide range of spectral types and are evenly distributed around the sky. This allows observations to be reduced relative to the standard stars using Bouguer's Law, provided that the filter set used is similar to that defining the standard system.

2.4 Photometers and Photomultipliers

The most important component of a photometer is the photomultiplier tube, which converts the photons collected by the telescope into a signal which may be analysed. This is achieved by directing the light on to a photocathode, which releases electrons by the photoelectric effect into the evacuated tube. These electrons are then accelerated and multiplied by a series of dynodes. The resultant electrons are collected by the anode. The most important characteristic of a photomultiplier is its linear response, i.e. the anode current is directly proportional to the number of photons striking the photocathode. The number of electrons collected at the anode for each electron released at the photocathode is known as the gain of the photomultiplier and can range from $10^6 - 10^9$. A more detailed description of the behaviour of photomultipliers is given by Lallemand (1962) and Zwicker (1977).

The electrons may be measured by two different techniques. The anode current may be amplified and then integrated by storage on a capacitor, whose charge is measured after some length of time. This method is known as DC integration and is most useful for bright stars. For fainter stars the method of pulse counting is preferable. In this method the group of $10^6 - 10^9$ electrons generated by one photoelectron is regarded as a single pulse and the number of pulses counted. Pulses below a certain level are eliminated by a discriminator. Normally a pulse lasts about 10^{-8} seconds and for bright stars overlapping of pulses can occur. A correction for this effect has to be made. If N is the observed number of counts per second, the number of counts lost is $N^2\tau$, where τ is the dead time and of the order of tens of nanoseconds. The relative merits of these methods are discussed by Baum (1962) and Rolfe and Moore (1970).

The major source of noise in photomultipliers is the release of electrons from the photocathode by thermionic emission. This is seen as the dark count or current measured when no light is falling on the photocathode. The dark current can be greatly reduced by cooling the photomultiplier and its housing (Young, 1963). This has the added advantage that any water vapour freezes on the housing rather than the cathode. More cooling is required for red-sensitive photomultipliers than those whose response peaks in the blue, since the electrons need less thermal energy to escape.

2.5 The Photometers used at S.A.A.O.

The St. Andrews photometer, designed by van Breda and Kelly (Kelly, 1977), employs pulse counting with integration times of 10, 30 and 60 seconds and was used at the f/15.8 Cassegrain focus of the 1m. Elizabeth telescope. Although equipped with both a blue EMI 6256 photomultiplier (S13 cathode) and a red EMI 9659 tube (extended S20 cathode), the channels cannot be used simultaneously, since a diagonal mirror in the light path of the blue tube feeds the red tube. The photomultipliers are operated in R.F. shielded water-cooled cold boxes. Filter and tube selection is controlled by a diode matrix on which the filter sequence is specified by the observer. The signal from the photomultiplier is passed through an

SSR amplifier and the counts are displayed on a teletype. The dead time is 57ns as determined by the staff at S.A.A.O. This value is supported by the lack of any discrepancies in the magnitudes derived in the next chapter. The time of observation and details of the filter and photomultiplier used are shown for each count.

DC integrating 'People's' photometers, with two optical paths leading to separate photomultipliers, were used at the f/18 Cassegrain focus of the 0.5m. and 1.9m. telescopes. These photometers may be used either for simultaneous star/sky measurements through two apertures or with two different filters using one aperture and a beamsplitter. Two EMI 6256 photomultipliers were used in R.F. shielded air-cooled cold boxes. The andode current is integrated using a double DC electrometer amplifier with two manual rotary gain controls. The coarse control has four positions at approximately 2.5 magnitude intervals, while the fine control has sixteen positions at approximately 0.25 magnitude intervals to give good overlap between coarse gain steps. Integration times of 30 and 120 seconds may be used. The DC signals from the two photomultipliers, when they have been equally amplified, can be displayed on a Brown recorder. Although the trace for only one of the signals can be shown during the integration, the integrated levels for both channels are displayed.

2.6 Filters

Before the light is collected by the photomultiplier, it is passed through an optical filter, which is usually either a compound glass filter or interference filter. Compound glass filters were the first type to be introduced and generally have wide or intermediate passbands. These are produced by covering a pair of glass surfaces with dielectric coatings and leaving a gap of the order of the wavelength of light between them. The precise separation determines the wavelengths passed by the filter and by coupling such etalons it is possible to remove unwanted orders. The minimum reflectivity is obtained using $\lambda/4$ coatings. Interference filters are mounted perpendicular to the light path through the photometer, since any tilt alters the effective wavelength of the filter. Details of the theory and construction of interference filters can be found in MacLeod (1969).

Strömgren (1963) divided filters into three classes according to the halfwidth, which is the width of the filter passband at half maximum transmission. The types are wide filters with halfwidths greater than 300A, narrow filters with halfwidths less than 100A and intermediate filters with halfwidths between these values. These definitions will be followed. The efficiency of a photometric system is determined by the narrowest filter and a system with both narrow and intermediate filters is described as a narrow band system.

CHAPTER 3

STRÖMGREN PHOTOMETRY

3.1 The Strömgren uvby System

a) Introduction

Strömgren (1966) proposed a filter system especially suited to the study of A, F and G-type stars which has been extended to include O and B stars. The system consists of four intermediate bandpass filters whose central wavelengths and halfwidths are given in Table 3.1. The transmission curves for the standard filters, as given by Matsushima (1969), and the actual filters used are shown in Fig. 3.1. While the u filter is a glass filter, the other filters are interference filters.

Table 3.1 Central Wavelengths and Halfwidths of Strömgren Filters

Filter	Central Wavelength (A)	Halfwidth (A)
u	3500	380
v	4100	200
b	4700	100
y	5500	200

The u and v filters are placed either side of the Balmer jump of hydrogen, which is probably the most important feature in the spectra of early-type stars. The only major line to fall within the bandpasses of the filters for early-type stars is $H\delta$, which lies in the v bandpass.

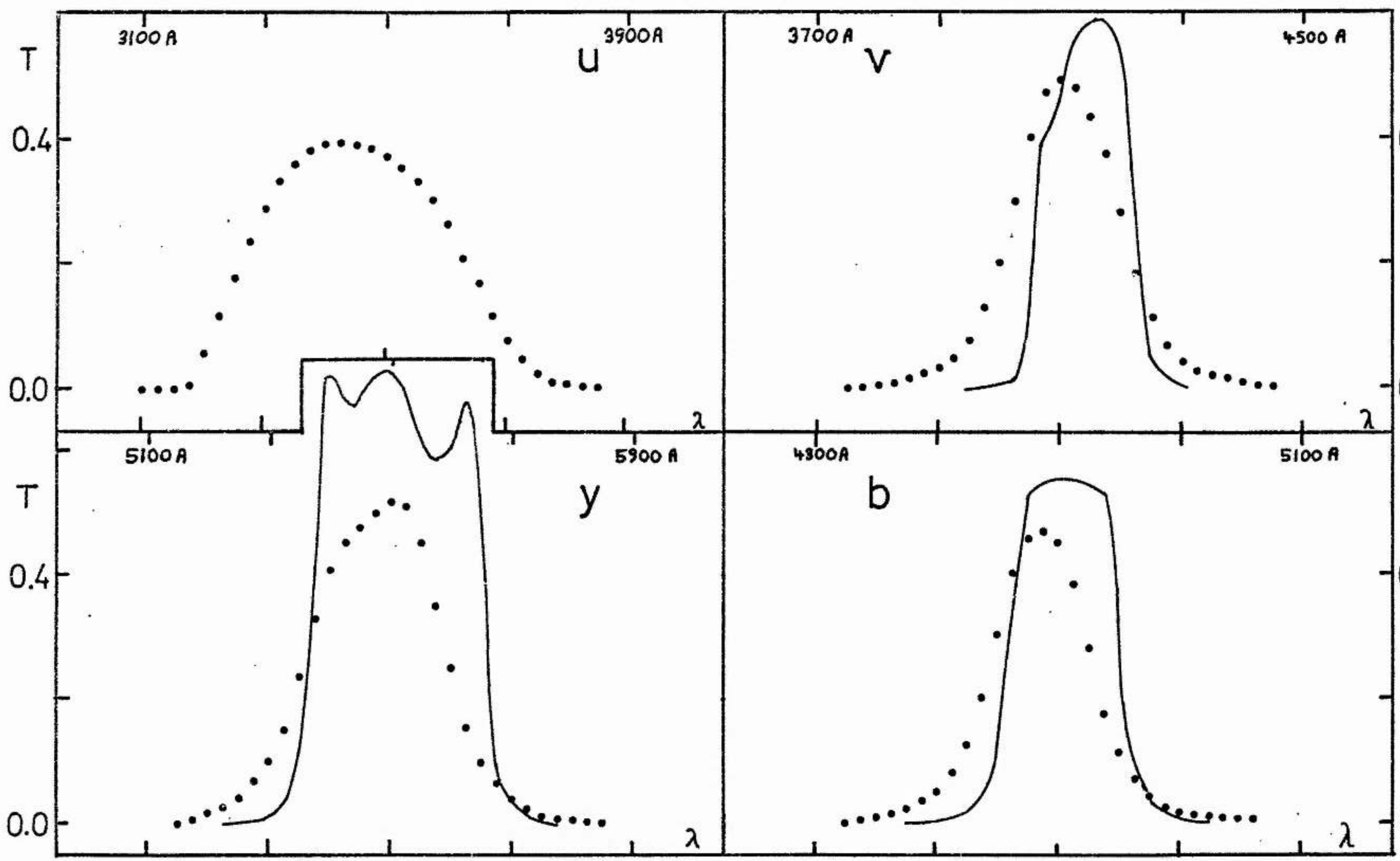


Figure 3.1 Transmission Curves of Strömgren Filters

Dots - standard filters Full line - filters actually used

Four main quantities are derived from uvby observations:-

i) the y filter provides an apparent magnitude which is equivalent to the V magnitude of the UBV system.

ii) the (b-y) colour provides a basic temperature parameter and represents a measure of the slope of the Paschen continuum.

iii) the colour difference $c_1 = (u-v) - (v-b)$ is a measure of the size of the Balmer discontinuity and hence luminosity for any given temperature. Since the line blocking in the u filter is approximately twice that in the v filter and the b filter is relatively free of lines, the c_1 index is almost independent of chemical composition effects.

iv) the colour difference $m_1 = (v-b) - (b-y)$ provides a measure of line blocking and hence metallicity.

A further non-independent quantity is the colour (u-b) which may be defined as

$$(u-b) = c_1 + 2(m_1 + (b-y)).$$

The primary standard stars for the system are given by Crawford and Barnes (1970), who showed that the system was determined purely by the filters. The system is independent of telescope, photometer and observing site when reduced to outside the atmosphere. Since all the filters are positioned well within the transparent region of the atmosphere, the thresholds of the response curves are not dependent on the Earth's atmosphere as is the case with the UBV system (Johnson, 1963). Due to the widths of the filters, reduction is simplified since colour effects on the slope of Bouguer's law are negligible.

b) Interstellar Reddening in the Strömgren System

The band widths of the uvby filters are narrow enough to make the reddening lines practically straight and dependent only on the adopted interstellar extinction law. Several astronomers have derived differing reddening relations between the Strömgren indices but Crawford (1975) has given values derived from observations of O stars, which will be used for all the following work. The relations are

$$E(m_1) = -0.32\ E(b-y)$$
$$E(c_1) = 0.20\ E(b-y)$$
$$E(u-b) = 1.54\ E(b-y)$$

In addition $E(b-y) = 0.74\ E(B-V)$, which if the ratio of total to selective absorption, $A_V/E(B-V)$, is taken to be 3.2, leads to

$$A_V = 4.3\ E(b-y).$$

From these relations it is possible to define the reddening free parameters

$$c_0 = c_1 - E(c_1) = c_1 - 0.20\ E(b-y)$$
$$m_0 = m_1 - E(m_1) = m_1 + 0.32\ E(b-y)$$

and $$(u-b)_0 = (u-b) - E(u-b) = (u-b) - 1.54\ E(b-y).$$

If $E(b-y)$ cannot be evaluated due to uncertainty in the intrinsic $(b-y)$ colour, it is still possible to remove the effect of interstellar reddening with the relations

$$[c_1] = c_1 - 0.20\ (b-y)$$
$$[m_1] = m_1 + 0.32\ (b-y)$$

and $$[u-b] = (u-b) - 1.54\ (b-y).$$

Osmer and Peterson (1974), Philip and Newell (1975) and Davis and Shobbrock (1977) have all shown that [u-b] is well related to temperature for the range $-0.1 \leq [u-b] \leq +1.4$.

c) Intrinsic Colours in the Strömgren System

In order to interpret the results of Strömgren observations, it is important to know the positions occupied by various types of star in photometric diagrams. Of major importance are the positions of unreddened main sequence stars and, in our case, the areas in which the different types of faint blue star occur. With a knowledge of both these positions and the effect of reddening, it should be possible to interpret the position occupied by the stars in the $c_1 - (b-y)$ and $m_1 - (b-y)$ diagrams and classify them accordingly.

Intrinsic colours for main sequence stars have been determined by Crawford (1978) and Crawford (1975a) for B and F stars respectively. No recent determination of intrinsic colours for A stars is available but Crawford (1970) gives a set of preliminary values.

Sargent and Searle (1968) gave spectroscopic classification criteria for faint blue stars and, from uvby observations of stars classified by these criteria, Graham (1970) defined the uvby classification properties of faint blue stars. The areas occupied by different groups of stars and the intrinsic colour lines are shown on the transparent overlays to Figs. 3.5 and 3.6. These overlays are based on diagrams by Kilkenny and Hill (1975) with only slight alterations.

3.2 uvby Observations

Strömgren observations were obtained using the S.A.A.O. 1m., 0.5m. and 1.9m. telescopes. The 1m. telescope was used with the St. Andrews photometer in its pulse counting mode during 1976 July, August and September and 1977 February and September. The 0.5m. telescope was used with a conventional DC-integrating 'People's' photometer during 1976 August and 1977 February while the 1.9m. telescope was used with a similar photometer during 1976 November.

The filter sequence generally used was ybvu uvby for the star and then ybvu for the sky. For fainter stars multiples of these sequences were employed until the required precision, 10^4 counts above sky, was reached. Usually between ten and twenty standards, taken from the lists of Crawford and Barnes (1970) and Grønbech and Olson (1976), were observed each night. Standard stars were observed at least once an hour and usually in pairs to reduce the possibility of one bad observation hindering the reductions. They were chosen to give as wide a range as possible in all indices. The standard stars used along with their photometric indices are listed in Table 3.2. Crawford and Barnes (1970) give no V magnitude for their standards and the assumed V magnitudes are those taken from a combination of the results of Johnson et al. (1966), Cousins (1973) and Grønbech and Olson (1976). To aid the determination of extinction coefficients, some standards were followed over a range of airmass, if this was possible.

The programme stars observed were part of the compilation, taken from proper motion and colour surveys, which was outlined by Kilkenny and Hill (1975). Some stars from the S2/68 ultraviolet

Table 3.2 Strömgren Standard Stars

Star	V	(b-y)	m_1	c_1
HR 531	4.659	0.209	0.184	0.648
HR 875	5.175	0.049	0.166	1.067
HR 1089	6.489	0.408	0.183	0.448
HR 1258	6.474	-0.081	0.099	0.182
HR 1292	5.707	0.231	0.163	0.592
HR 1861	5.343	-0.077	0.074	-0.002
HR 2056	4.885	-0.076	0.121	0.408
HR 2313	5.877	0.359	0.170	0.394
HR 2360	6.268	-0.061	0.114	0.540
HR 2590	4.655	0.248	0.150	0.649
HR 2679	6.498	0.000	0.036	-0.134
HR 2707	5.441	0.184	0.187	0.878
HR 2961	4.842	-0.082	0.100	0.304
HR 3131	4.609	0.049	0.158	1.128
HR 3459	4.615	0.519	0.289	0.476
HR 3849	5.072	-0.069	0.107	0.405
HR 4119	5.082	-0.064	0.116	0.466
HR 4695	4.970	0.720	0.485	0.513
HR 5011	5.193	0.376	0.191	0.383
HR 5059	5.971	0.095	0.202	0.977
HR 5270	6.210	0.633	0.090	0.550
HR 5530	5.155	0.262	0.155	0.497

Star	V	(b-y)	m_1	c_1
HR 5660	4.918	0.244	0.136	1.381
HR 6141	4.794	-0.046	0.085	0.202
HR 6219	5.587	0.020	0.023	-0.102
HR 6595	4.870	0.301	0.150	0.413
HR 6930	4.692	0.043	0.145	1.213
HR 7446	4.949	0.079	-0.014	-0.022
HR 7560	5.130	0.356	0.188	0.404
HR 7610	5.280	0.002	0.174	1.020
HR 7773	4.764	-0.022	0.135	1.025
HR 7858	5.398	0.038	0.196	0.975
HR 8060	4.859	0.088	0.186	0.949
HR 8551	4.791	0.638	0.426	0.404
HR 8826	5.164	0.075	0.165	1.090
HR 9006	5.181	-0.085	0.101	0.290
HR 9091	5.040	-0.067	0.107	0.461

survey (Boksenberg et al., 1973) were also observed using finding charts provided by Giddings (1976).

3.3 Reduction Procedure

The observations are either in the form of pen traces with DC integration or counts in the case of pulse counting. They provide four numbers u′, v′, b′ and y′ when the sky values have been removed and corrections made for dead time or DC gain settings. For sky counts dead time corrections are negligible. The DC integration values were adjusted according to the amplifier gain stop used. The gain tables used for the 0.5m. and 1.9m. amplifiers were supplied by S.A.A.O.

Following the convention of Crawford and Barnes (1970) the reductions proceed in the following way. If X is the air mass of the mean hour angle for the observation, then the indices in the natural system of the photometer are given by

$$\begin{aligned} y_{obs} &= y' - KX \\ (b-y)_{obs} &= (b'-y') - K_1 X \\ (v-b)_{obs} &= (v'-b') - K_2 X \\ (u-b)_{obs} &= (u'-b') - K_3 X \end{aligned}$$

where K, K_1, K_2 and K_3 are the extinction coefficients. These values may then be transformed to the standard system by the formulae

$$\begin{aligned} V &= A + y_{obs} + B(b-y) \\ (b-y) &= C + D(b-y)_{obs} \\ (v-b) &= E + F(v-b)_{obs} + J(b-y) \end{aligned}$$

$$(u-b) = G + H(u-b)_{Obs} + I(b-y)$$

The quantities D, F and H are the scale factors and A, C, E and G are the zero points. The V magnitude scale factor is taken to be unity. The colour term coefficients, B, J and I, are evaluated at a later stage and are discussed in Section 3.4.

The reduction program is one in general use at St. Andrews and was supplied to Dr. R.W. Hilditch by Dr. G. Hill, D.A.O. The program calculates a least squares solution for scale factors, extinction coefficients and zero points for V, (b-y), (v-b) and (u-b) from the standard star observations.

On nights with few standards the determination of scale factors and extinction coefficients can prove difficult and mean values from the nights with reasonable numbers of standard stars have been used in certain cases. Mean scale factors were used for 1976 November 1/2, 6/7 and 9/10 on the 1.9m. telescope and 1977 September 21/22 on the 1m. telescope. Mean extinction coefficients were also used for the three November nights on the 1.9m. telescope. Two sets of Strömgren filters were used, the change taking place between the 1977 February and May observations.

The values determined for the scale factors, extinction coefficients and zero points are listed in Table 3.3.

3.4 Analysis of Residuals

a) Method

The standard star residuals, that is the differences between the standard and observed indices for each star, were checked for any systematic effects. The effects investigated were variations with

Table 3.3 Derived Scale Factors, Extinction Coefficients and Zero Points for Strömgren Photometry

Date	Telescope	Scale Factors			Extinction Coefficients				Zero Points			
		D[b-y]	F[v-b]	H[u-b]	K[V]	K_1[b-y]	K_2[v-b]	K_3[u-b]	A[V]	C[b-y]	E[v-b]	G[u-b]
1976 July 10/11	1m.	1.074	1.056	1.010	0.108	0.062	0.114	0.397	19.580	0.350	0.242	0.691
1976 July 11/12	1m.	1.069	1.052	1.012	0.098	0.051	0.109	0.399	19.574	0.333	0.233	0.687
1976 Aug 12/13	1m.	1.053	1.041	1.012	0.118	0.044	0.111	0.397	19.556	0.302	0.252	0.689
1976 Sept 3/4	1m.	1.067	1.029	1.009	0.136	0.057	0.126	0.431	19.574	0.323	0.261	0.715
1976 Sept 6/7	1m.	1.068	1.024	1.010	0.140	0.050	0.081	0.404	19.559	0.304	0.193	0.655
1977 Feb 2/3	1m.	1.074	1.041	1.018	0.119	0.070	0.133	0.391	19.724	0.361	0.269	0.628
Mean Values		1.068	1.041	1.012	0.120	0.056	0.112	0.403				
Standard Deviation		0.008	0.012	0.003	0.016	0.009	0.018	0.014				
1977 May 10/11	0.5m.	1.031	0.960	0.998	0.123	0.040	0.125	0.354	3.431	0.752	-0.076	0.417
1977 Sept 21/22	1m.	Mean Values used			0.104	0.090	0.131	0.422	19.270	0.756	-0.068	0.548
1977 Sept 22/23	1m.	1.063	0.973	0.995	0.160	0.051	0.138	0.396	19.352	0.709	-0.054	0.507
Mean Values		1.047	0.967	0.997	0.129	0.060	0.131	0.391				

time, colour, air mass, hour angle, declination and V magnitude.

A FORTRAN program was written using the GHOST plotting routines (Morrison, 1973) with the IBM 360/44 computer and C.I.L. 6011 plotter of the University of St. Andrews Computing Laboratory. The residuals were plotted against the dependent variable and a least squares linear fit calculated. In the case of temporal variations a quadratic least squares solution was also calculated. A visual check was made of each plot for any variations which could not be represented by the plotted linear or quadratic fits.

An initial temporal check was made in case a strong time drift was present and then colour effects were investigated. Correction for colour terms was sometimes found to introduce slight variations with air mass. No effects were found with hour angle, magnitude or declination. A final check was then made for any remaining time drifts.

b) Colour Terms

Plots of standard star residuals during the period 1976 July - September for V, (v-b) and (u-b) against (b-y) are shown in Figs. 3.2, 3.3 and 3.4. The residuals are shown without any corrections and time drifts will have increased the spread of the points. Colour effects are seen in V and (v-b). The V colour term is essentially linear and increased steadily from 0.031 in 1976 July to 0.055 in 1977 February, after which a new filter set was used. The new V filter also shows a linear colour term with a mean gradient of 0.037. The (v-b) colour effect is strongly non-linear

Figure 3.2 V Magnitude Residual - (b-y) Diagram for Standard Stars

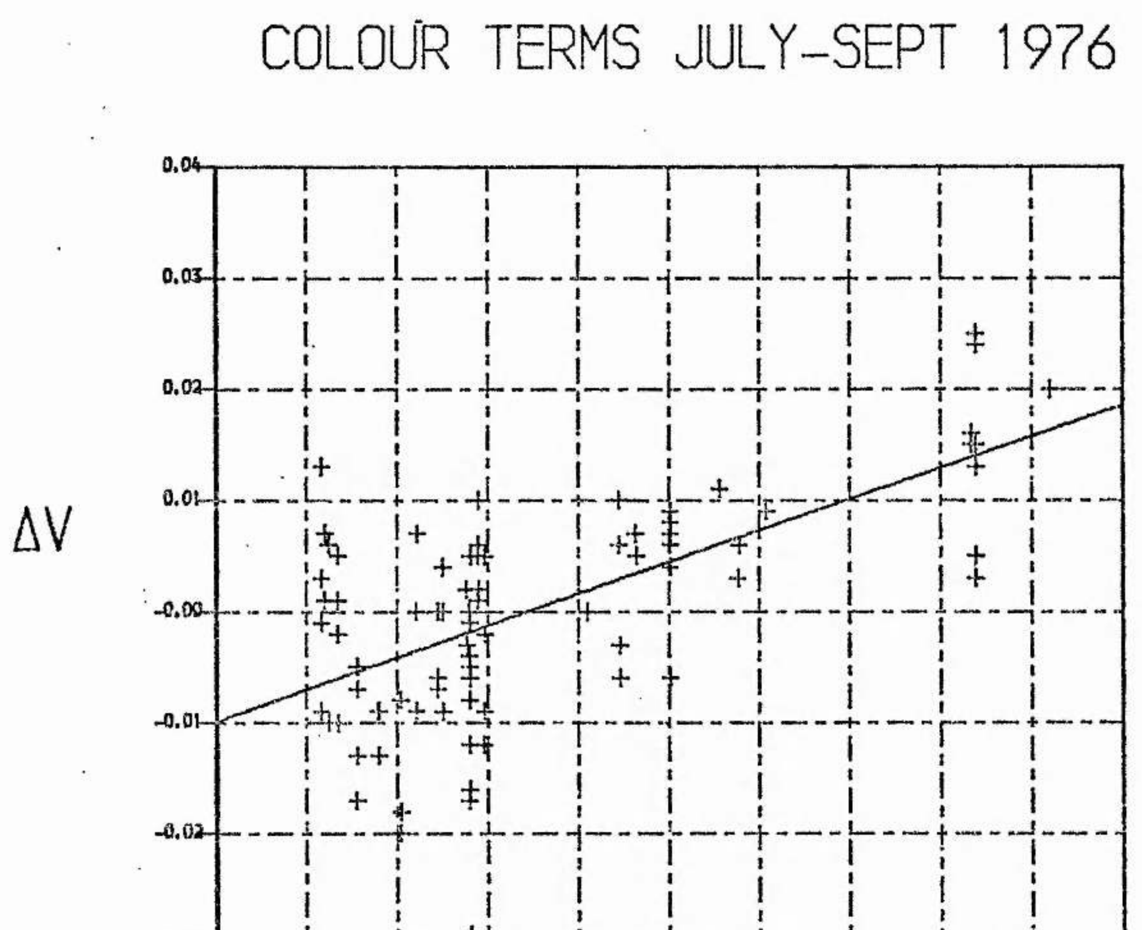


Figure 3.3 (v-b) Residual - (b-y) Diagram for Standard Stars

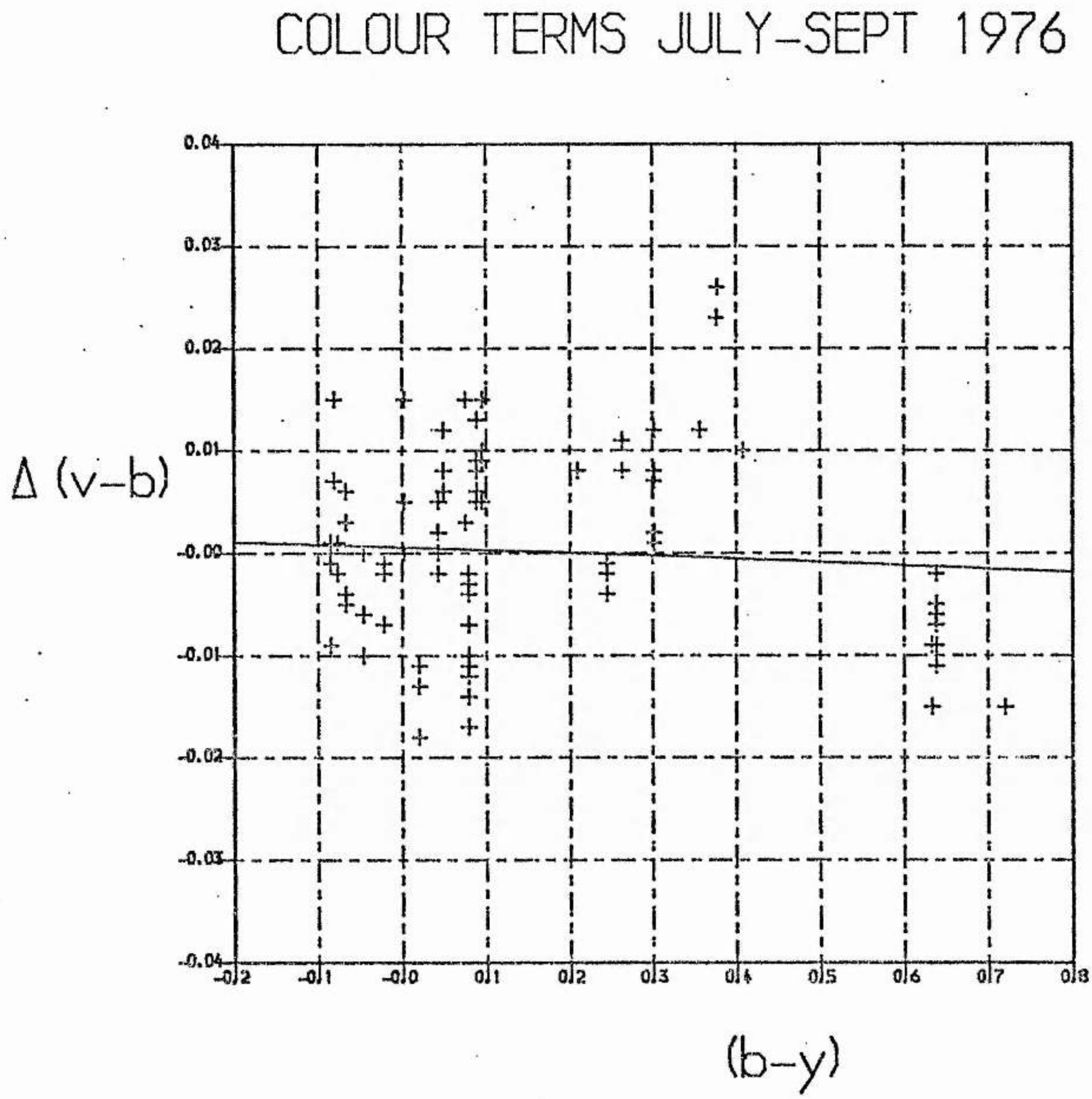
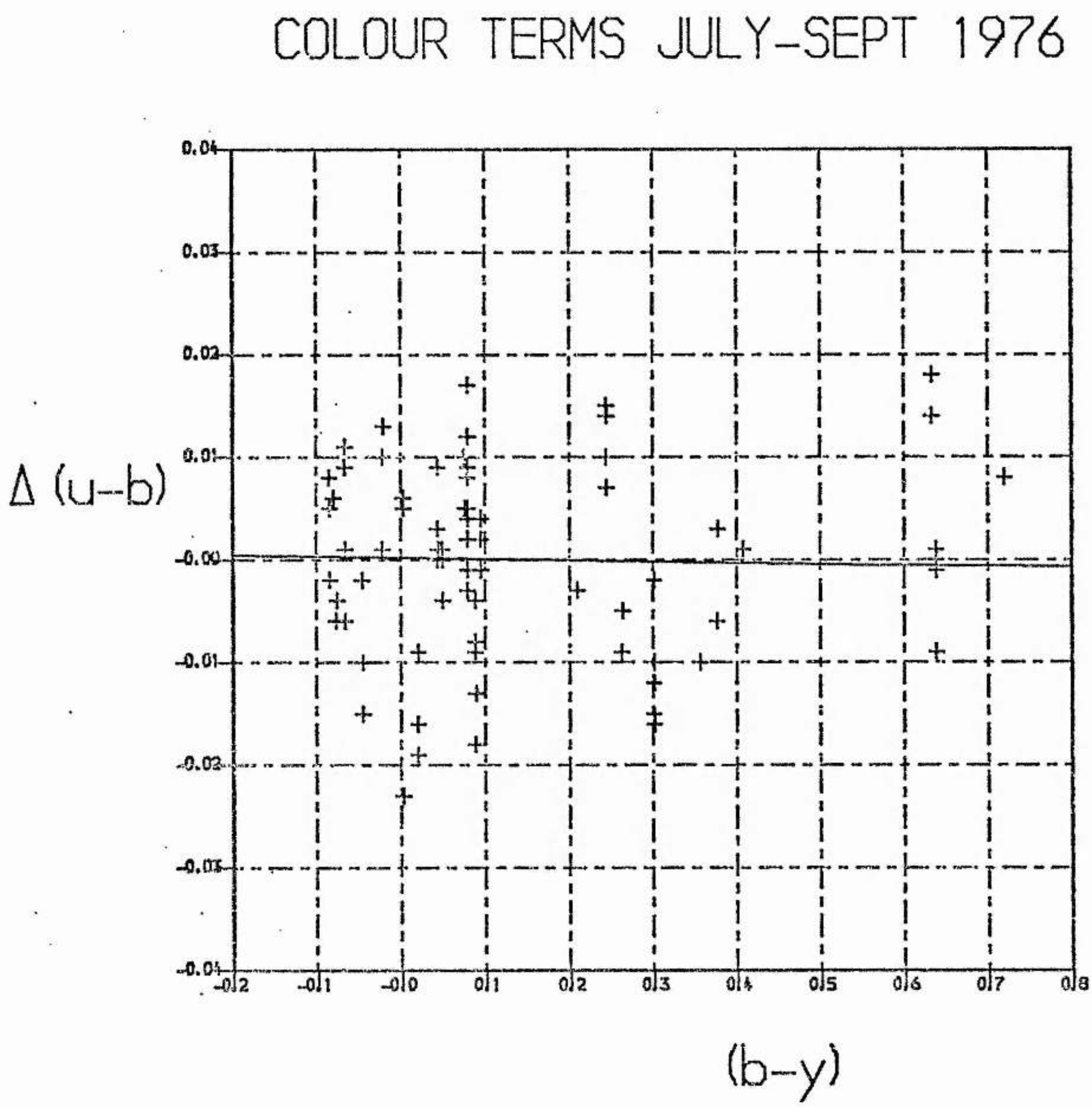


Figure 3.4 (u-b) Residual - (b-y) Diagram for Standard Stars



and resulted in the removal of all stars with $(b-y) > 0.41$ from the (v-b) reductions. For the remaining stars the effect was reasonably linear. No (v-b) colour effect is seen with the new filter set. No colour effects were found in the (u-b) residuals.

c) Effects with Air Mass

The V colour effect was responsible for a distortion in the evaluation of the V extinction coefficient. After the colour effect was removed, a variation of V residual with air mass was found with a mean gradient of -0.019 ± 0.09 from six nights.

d) Time Drifts

It was exceptional for no temporal zero point variation to be present, although the magnitude of the corrections needed was rarely greater than $0^m.015$ in V where the effect was greatest. In the colours the zero point drifts were usually negligible compared with the error in a single observation.

3.5 Results

a) Errors

A comparison of the observations from the three telescopes was made. The mean differences between the 1m. and 0.5m. observations (1m. - 0.5m.) were $\Delta V = +0.007 \pm 0.008$(s.d.), $\Delta(b-y) = -0.008 \pm 0.011$, $\Delta m_1 = -0.001 \pm 0.006$ and $\Delta c_1 = +0.010 \pm 0.037$ for five stars. For the seven stars common to the 1m. and 1.9m. telescopes the mean differences (1m. - 1.9m.) were $\Delta V = -0.007 \pm 0.014$(s.d.), $\Delta(b-y) = +0.001 \pm 0.013$, $\Delta m_1 = +0.006 \pm 0.024$ and $\Delta c_1 = -0.006 \pm 0.048$.

These differences show that there is little disagreement between the observations obtained with each telescope and no corrections were made before combining the photometry.

Excluding PHL 1434 and CD-31°4800, which are probably variable in V, and PHL 8667 which may be variable in c_1, the combined data gives standard deviations for a single observation of ±0.014 in V, ±0.011 in (b-y), ±0.016 in m_1 and ±0.021 in c_1. These values were obtained from 89 observations of the 34 stars with more than one observation, using the formula

$$\sigma^2 = \frac{\sum (n_* - 1)\,\sigma_*^2}{\sum (n_* - 1)} \qquad \text{summed over all the stars}$$

where σ, σ_* and n_* are the standard deviation of a single observation, the standard deviation for each star and the number of observations per star.

b) The Programme Star Photometry

The Strömgren photometry for the programme stars is listed in Table 3.4. The first two columns contain the star name and any alternative name. The subsequent columns contain galactic coordinates, values for V, (b-y), m_1 and c_1 and the number of observations for each star. The final three columns contain the estimated spectral type from the photometry, any previously published spectral types and their sources. The references cited in the final column are:-

(1) Greenstein and Sargent (1974)

(2) Hill (1970)

(3) MacConnell et al. (1972)

(4) Feast, Thackeray and Wesselink (1960)

(5) Newell (1973)

An asterisk preceding an entry indicates a note following the table. The $m_1 - (b-y)$ and $c_1 - (b-y)$ diagrams for the programme stars are shown in Figs. 3.5 and 3.6. The transparent overlays show the classification zones and intrinsic colour lines, as discussed in Section 3.1c.

c) Comparison with Published Photometry

Ten of the brighter stars have published UBV photometry. Blanco et al. (1968), Hill and Hill (1966), Hill (1970) and Penston (1973) each give values for three stars, while MacConnell et al. (1972) and Eggen (1973) give values for two stars and one star respectively. The mean difference in V magnitude in the sense (my values - others) is -0.015 ± 0.044(s.d.) but this is largely due to the values given by MacConnell et al. and if these are excluded the mean difference is -0.004 ± 0.033. These figures indicate that the derived V magnitudes are unlikely to be systematically wrong bearing in mind that the probable error in a single observation is ± 0.009.

The only star for which published Strömgren photometry exists is HD 125924. Newell and Graham (1976) give values from which the largest difference is 0.013 in c_1.

Table 3.4 Strömgren Photometry for Programme Stars

	Star	Alternate name	l	b	V	(b-y)	m_1	c_1	n	Photometric classification	Spectral type	Ref.
	JL 163		318.88	-65.59	12.90	0.340	0.168	0.314	1	Late F		
*	LB 3130		307.16	-44.89	12.71	0.036	0.107	1.064	1	Ahb		
	LB 3134		310.07	-54.49	12.52	0.047	0.134	1.264	1	Ahb		
	JL 198		310.42	-67.79	10.23	0.321	0.168	0.394	1	F6		
	LB 3162		303.36	-55.73	12.03	0.214	0.176	0.693	1	Late A		
	PHL 6807		123.85	-65.71	12.54	0.102	0.107	1.331	3	Ahb		
	LB 3176		300.32	-52.97	11.61	0.083	0.125	1.252	1	Ahb		
	LB 1591		296.42	-66.74	12.89	0.028	0.112	1.202	1	Ahb		
*	TS 195		272.49	-82.92	12.13	-0.081	0.122	0.282	3	B3(sd?)		
	PHL 3368	SB 619	159.10	-73.81	12.58	0.029	0.182	1.092	1	A1		
	PHL 8374		204.21	-65.73	12.50	0.003	0.146	1.251	1	Ahb		
*	PHL 1434		200.92	-63.57	12.58:	-0.090	0.124	0.192	2	B2(sd?)		
	LB 3286		285.75	-46.82	12.60	0.219	0.099	0.762	1	sdFG		

	Star	Alternate name	l	b	V	(b-y)	m_1	c_1	n	Photometric classification	Spectral type	Ref.
	LB 1652	CD-47°950	259.08	-57.07	12.46	-0.003	0.135	1.055	1	A0		
*	PHL 8667		191.40	-48.15	11.51	0.369	0.184	0.311:	2	Late F		
	PHL 1548		198.10	-49.98	13.36	-0.129	0.121	-0.197	1	sdO,DO		
*	TS 401		228.57	-46.87	12.30	-0.077	0.122	0.512	1	B6(Binary?)		
*	LB 3384	HD 270754	278.36	-36.79	11.29	0.123	0.013	-0.077	2	O9(sdB?)	B1.5Ia	(4)
*	BD-17°3883	FB 134	316.67	43.22	9.06	0.059	0.122	1.199	3	Ahb	Hb	(1)
*	Abell 36	FB 138	318.44	41.50	11.57	-0.127	0.052	-0.239	2	sdO,DO	sdO	(1)
	BD-2°3766	FB 141	333.98	55.83	10.28	-0.084	0.089	0.073	2	B1	'Normal'	(1)
	HD 125924	FB 146	338.13	48.28	9.66	-0.095	0.092	0.077	3	B1.5	B2IV	(2)
	HD 127493	FB 150	331.46	34.57	10.03	-0.113	0.050	-0.206	4	sdO,DO	sdO	(1)
	HD 130095		332.30	28.97	8.13	0.067	0.095	1.282	2	Ahb	A0V,Hb	(2),(5)
*	L 839-50		347.07	35.22	13.58	0.384	0.117	0.613	1	F		
	HD 139961		332.02	8.03	8.85	0.078	0.122	1.294	3	Ahb	Hb	(5)
*	BD-9°4395		6.02	26.02	10.55	0.123	0.002	-0.069	3	O9(sdB?)	H-poor	(3)

Star	Alternate name	l	b	V	(b-y)	m_1	c_1	n	Photometric classification	Spectral type	Ref.
* HD 150055		345.26	6.23	10.94	0.196	0.107	1.039	3	B9.5		
* BD-1°3438		26.56	10.08	10.30	0.388	0.025	0.281	4	sdFG	H-poor	(3)
* JL 6		324.68	-26.21	13.87	-0.122	0.155	0.302	1	B2(sd?)		
JL 25		318.63	-29.17	13.33	-0.079	0.066	-0.241	3	sdB,DB		
JL 36		323.10	-31.13	12.98	-0.043	0.074	0.048	3	B1		
JL 62		318.23	-33.38	11.39	-0.016	0.061	0.428	3	B5		
PHL 1580		31.36	-43.49	12.33	-0.076	0.048	0.045	3	B1		
PHL 44		39.31	-42.36	13.25	-0.126	0.118	-0.023	1	sdB		
PHL 48		47.08	-39.42	13.52	-0.093	0.095	0.090	1	B2		
PHL 4748		40.51	-43.54	12.83	0.016	0.085	1.116	2	Ahb		
PHL 110		42.23	-43.48	13.09	0.017	0.082	0.866	1	B9		
LB 10000		303.29	-27.52	12.26	0.377	0.122	0.474	2	F(sd?)		
JL 87		315.00	-36.14	12.03	-0.027	0.082	-0.062	1	B0(sd?)		
PHL 159		58.93	-37.30	10.76	-0.073	0.088	0.144	4	B1.5		

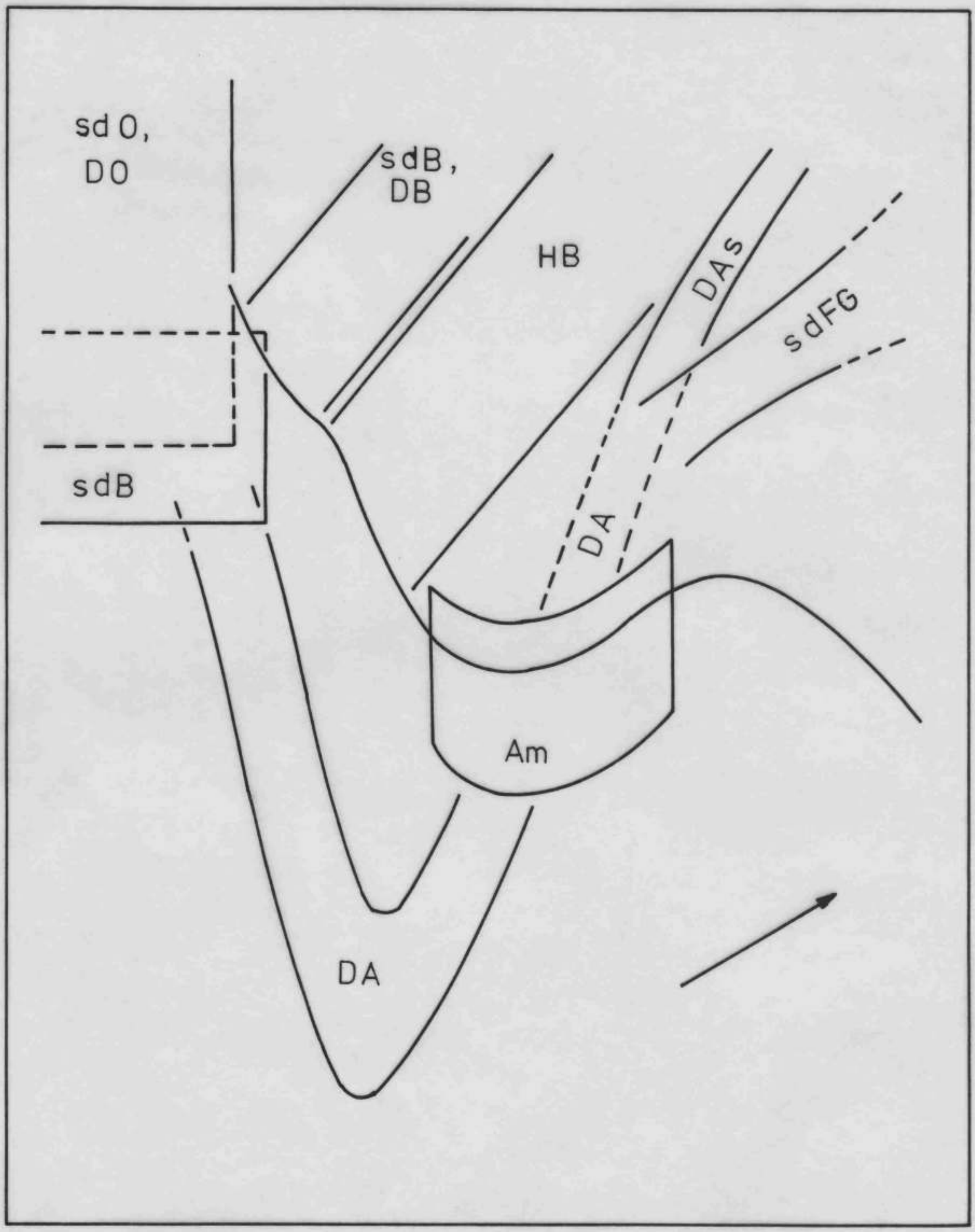
	Star	Alternate name	l	b	V	(b-y)	m_1	c_1	n	Photometric classification	Spectral type	Ref.
	PHL 178		31.21	-48.65	13.06	-0.118	0.047	-0.237	1	sdO,DO		
	PHL 227		65.50	-43.41	13.49	0.059	0.047	0.080	2	B1		
*	LB 1502		350.24	-56.06	13.02	-0.052	0.124	0.833	3	B9(?)		
	PHL 1957		61.84	-49.47	11.96	0.014	0.107	0.996	2	B9.5(hb?)		
*	PHL 334	TS 61	15.85	-60.36	13.17	-0.144	0.082	-0.127	2	sdB		
*	PHL 5382		29.65	-60.40	12.53	-0.061	0.129	0.588	1	B7		
*	PHL 375		69.91	-47.86	11.91	-0.036	0.187	0.538	3	B7(sd?)		
	LB 1514		340.58	-58.86	13.04	0.012	0.102	1.208	1	Ahb		
*	JL 124		309.66	-37.85	13.66	0.016	0.088	0.085	1	sdB		
	JL 129		306.38	-33.58	13.55	0.250	0.015	-0.288	1	DA(?)		
	PHL 460		40.88	-68.64	12.24	-0.069	0.106	0.426	2	B5		
	PHL 5882		72.94	-63.13	11.61	0.071	0.210	1.011	2	A(m?)		
	PHL 2408		49.17	-72.01	10.94	0.047	0.116	1.302	1	Ahb		
	LB 1529		322.49	-58.81	12.95	0.033	0.162	1.283	2	Ahb		

Star	Alternate name	l	b	V	(b-y)	m_1	c_1	n	Photometric classification	Spectral type	Ref.
LB 1538		323.20	-65.13	12.14	0.046	0.132	1.296	1	Ah'b		
PHL 610		32.54	-78.36	13.50	-0.079	0.085	-0.192	1	sdB,DB		
* BD-13°842		206.48	-40.56	11.99	-0.276	0.354	-0.376	2	sdOp,DOp		
* CD-31°4800		246.46	- 5.51	10.55	-0.144	0.058	-0.180	2	sdO,DO		
BD-3°2179		224.81	13.79	10.35	-0.140	0.074	-0.208	2	sdO,DO		
HD 76431		226.72	28.27	9.24	-0.130	0.083	-0.086	1	sdO,DO		
HD 171858		10.70	- 7.55	9.86	-0.109	0.093	-0.027	2	sdB		
* HD 188112		12.63	-25.42	10.21	-0.118	0.142	0.099	2	B1.5(sdB?)		
CD-35°15910		1.89	-73.87	10.96	-0.141	0.111	-0.041	2	sdB		

Notes to Table 3.4

LB 3130	c_1 low for hb, lies close to intrinsic colour line in c_1 - (b-y) diagram. Newell(1973) includes in his group A - the 'true' hb stars.
TS 195	Bluer than intrinsic colour line in m_1 - (b-y) diagram. Newell(1973) places this star between his HL and BC groups.
PHL 1434	$\Delta V = 0\overset{m}{.}07$, bluer than intrinsic colour line in m_1 - (b-y) diagram.
PHL 8667	$\Delta c_1 = 0\overset{m}{.}09$ from two observations.
TS 401	Bluer than intrinsic colour line in both diagrams.
LB 3384	Newell(1973) places in his HL group with $\Theta = 0.17$ and $\log g = 3.7$. This star entered this work from a Luyten(1962) proper motion list but is in fact an LMC B1.5Ia star (Feast, Thackeray and Wesselink, 1960).
BD-17°3883	Greenstein and Sargent(1974) remark 'Mg II strong for hb'.
Abell 36	Greenstein and Sargent(1974) remark 'He II strong'.
L 839-50	The position occupied by this star is unusual and suggests a highly reddened early F star.
BD-9°4395	Kaufmann and Schönberner(1977) showed this star to be a helium-rich giant star and deduced $E_{B-V} = 0.32$ from their final model. The differences between our photometry, when dereddened, and the theoretical results of Kaufmann and Schönberner are -0.012, -0.033, +0.122 and +0.032 for $(b-y)_o$, m_o, c_o and $(u-b)_o$. The agreement is not satisfactory.
HD 150055	This star has $E(b-y) \simeq 0.21$ due to its low galactic latitude.
BD-1°3438	MacConnell et al.(1972) have shown this star to be a reddened hydrogen-poor B star.
JL 6	Bluer than the intrinsic colour line in both diagrams; c_1 is greater than expected for an sdB.
LB 1502	Marginally bluer than intrinsic colour line in both diagrams.

PHL 334	Newell(1973) places in the hot extension to his D group.
PHL 5382	Marginally bluer than intrinsic colour line in both diagrams.
PHL 375	Significantly bluer than intrinsic colour line in m_1 - (b-y) diagram.
JL 124	Redder than normally expected for an sdB.
BD-13° 842	Central star of a planetary nebula with high surface brightness, inclusion of parts of the nebula has probably affected the photometry.
CD-31° 4800	$\Delta V = 0\overset{m}{.}06$ from two observations.
HD 188112	Bluer than the intrinsic colour lines in both diagrams.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DO
sdB,
DB
HB
DAs
sdFG
sdB
DA
Am
DA

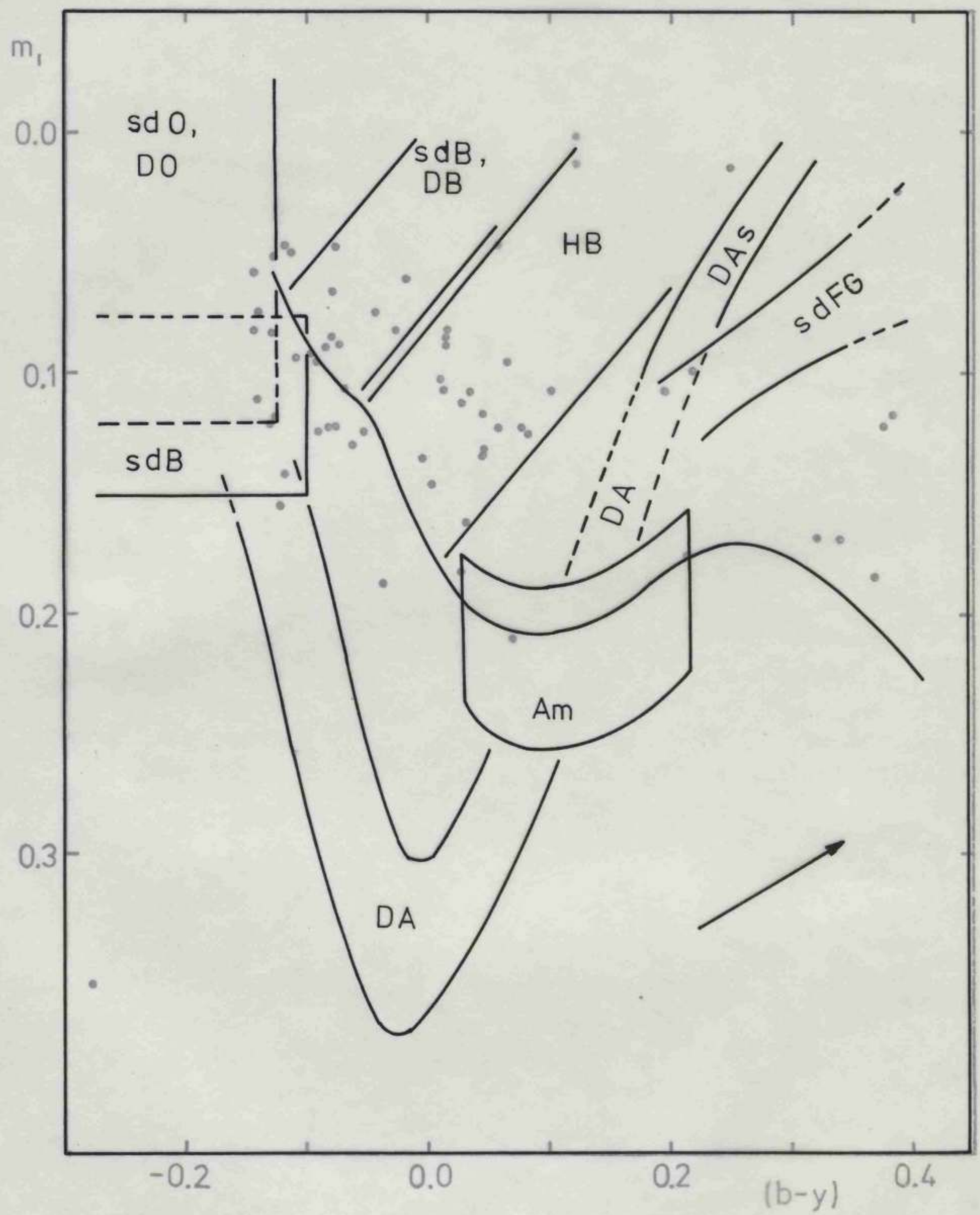


Figure 3.5 m_1 - (b-y) Diagram for Faint Blue Stars

with Overlay showing Classification Zones

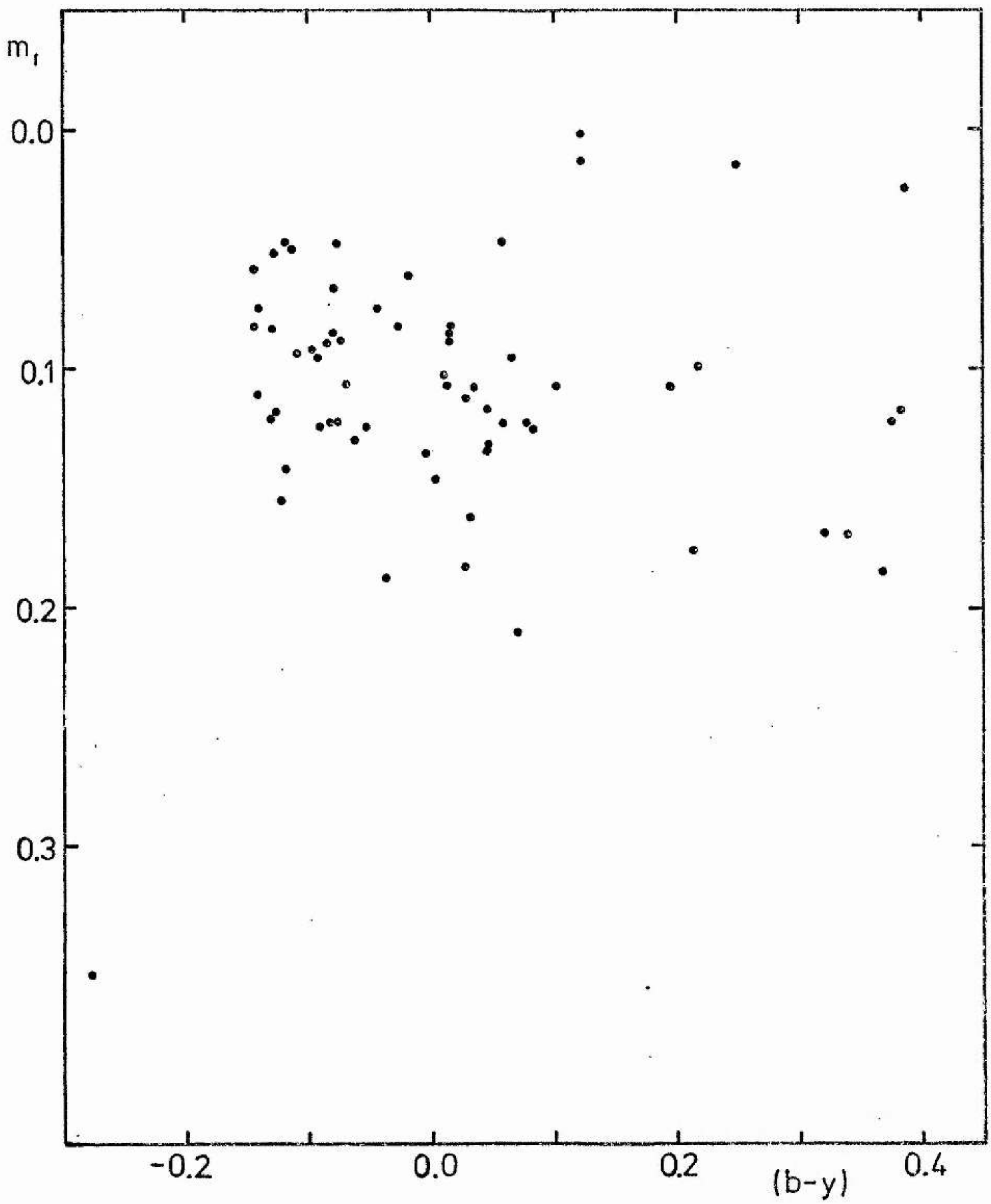
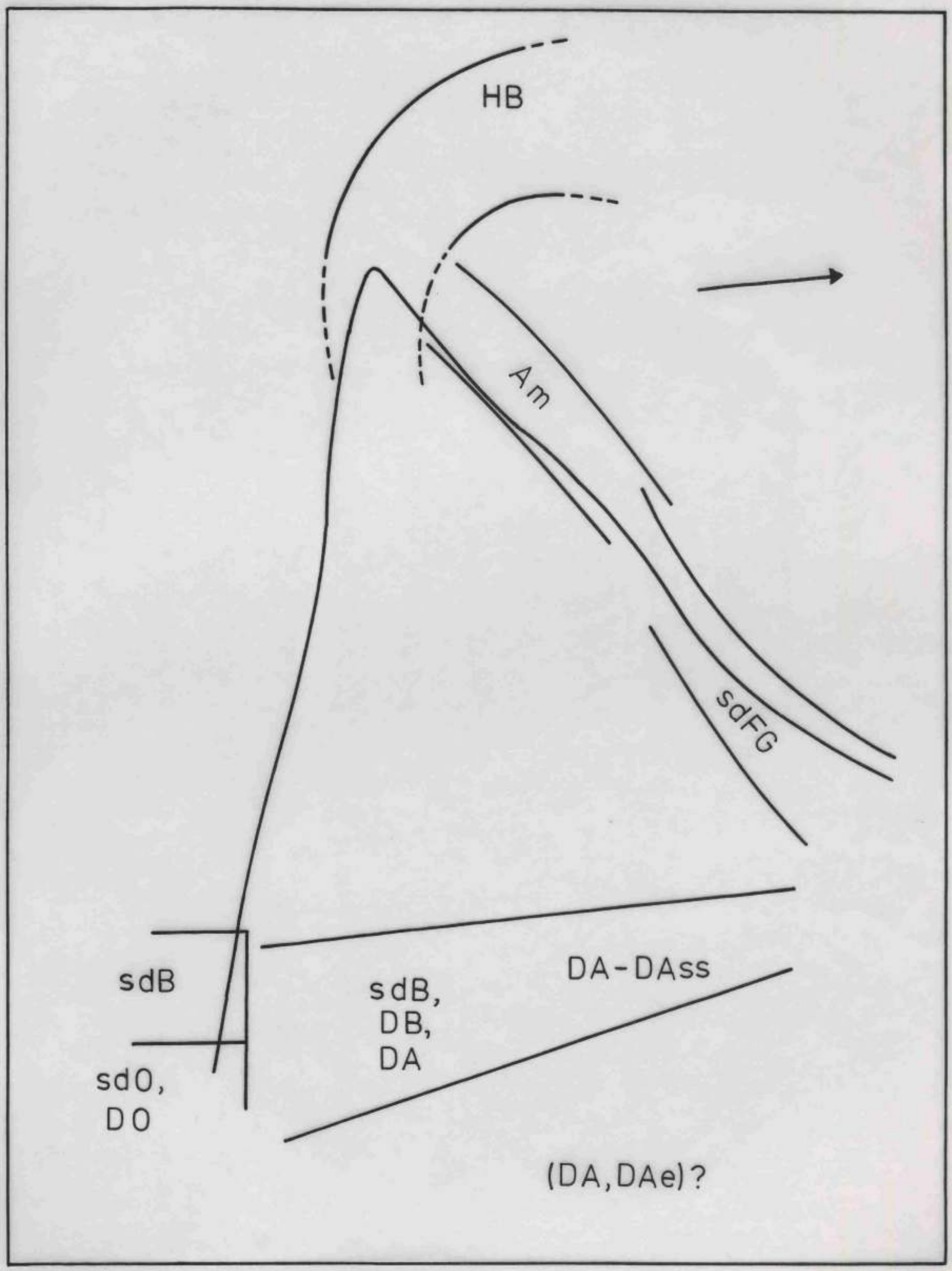


Figure 3.5 m_1 - (b-y) Diagram for Faint Blue Stars with Overlay showing Classification Zones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Am
sdFG
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DB,
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DA-DAss
sdO,
DO
(DA,DAe)?

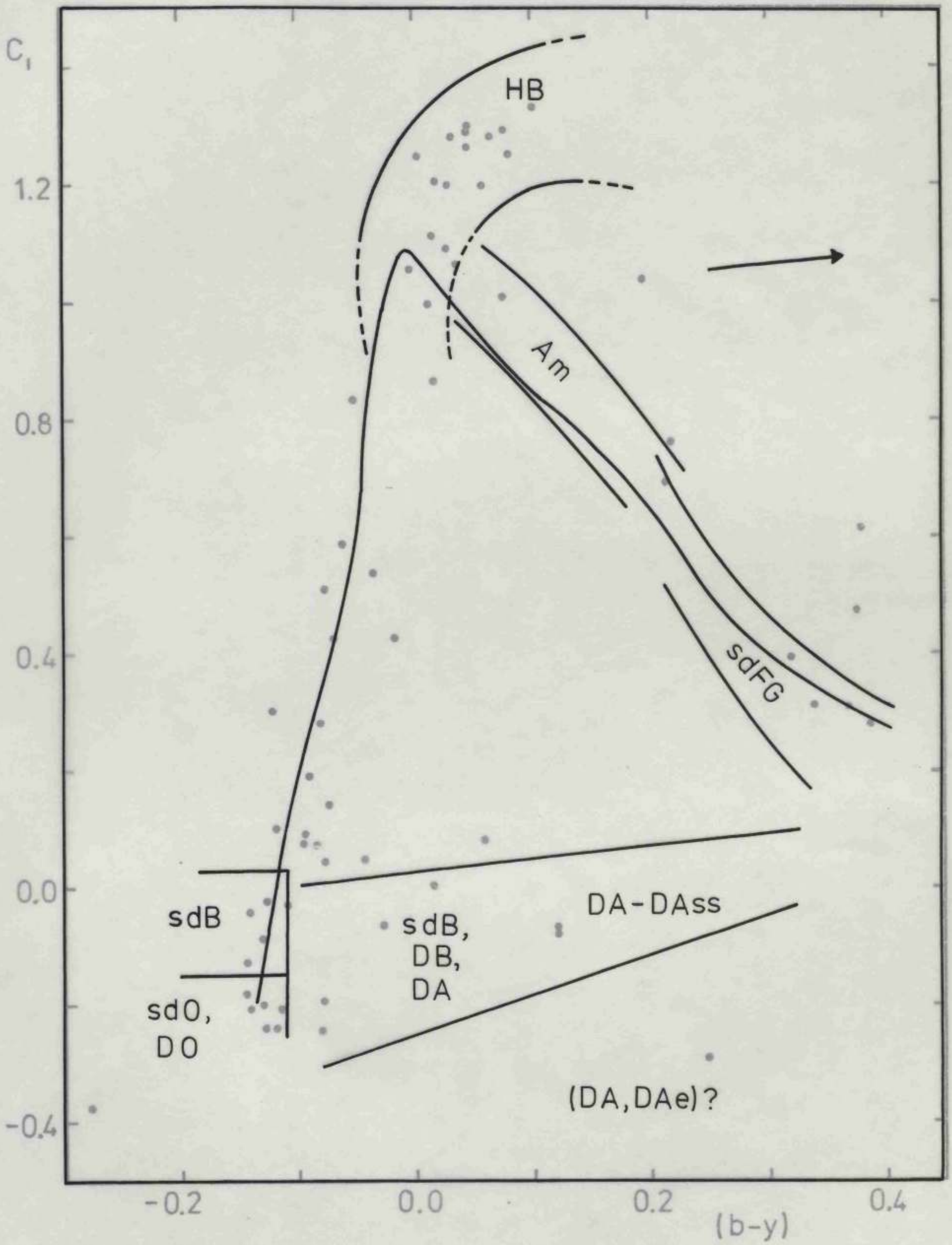


Figure 3.6 c_1 - (b-y) Diagram for Faint Blue Stars with Overlay showing Classification Zones

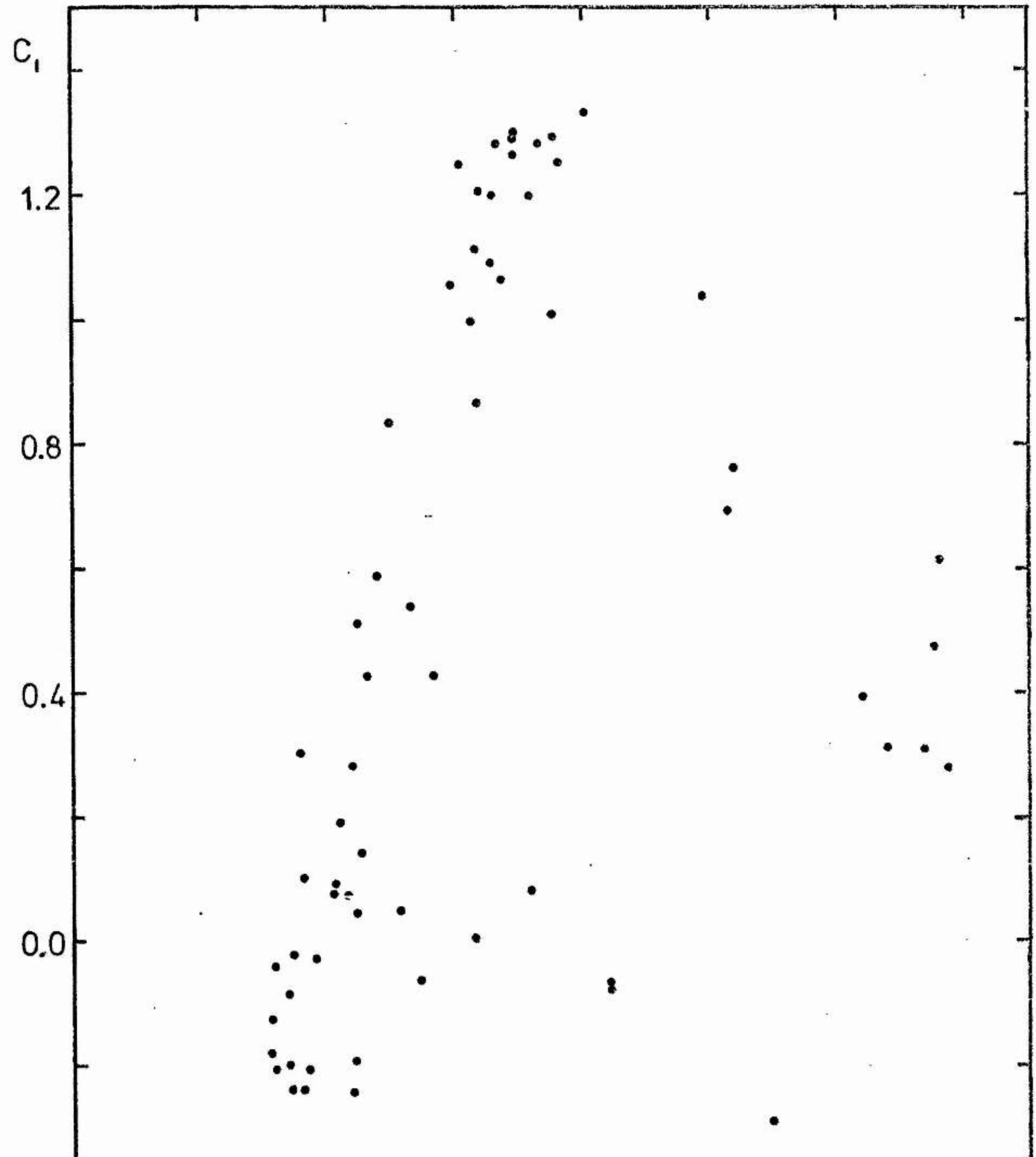


Figure 3.6 c_1 - (b-y) Diagram for Faint Blue Stars with Overlay showing Classification Zones

3.6 Classification Difficulties using Strömgren Photometry

Strömgren photometry provides a good general method of classification for normal stars, as can be seen from Section 3.5. The situation is simplified in the case of faint blue stars since reddening effects should be small. However this is not necessarily true for many faint apparently normal stars which appear to be at large distances.

Usually OB subdwarfs can be separated from main-sequence stars since the latter are normally reddened. However it would be difficult to separate an unreddened O-type dwarf from an sdO. The sdO and DO stars are indistinguishable when using Strömgren photometry and hot DA stars may also lie in the same area.

The sdFG stars are easily identifiable as are most horizontal branch stars. However it would appear (Kilkenny and Hill, 1975) that the horizontal branch stars extend across the intrinsic colour line for late B stars and could cause problems in classification. $H\beta$ photometry could provide information on such stars, as has been shown by Kilkenny (1977a) and Philip (1973). Unfortunately $H\beta$ photometry has an observational limit which is at least two magnitudes brighter than that of Strömgren photometry and this restricts its use.

Methods to alleviate the difficulties due to the restrictions on $H\beta$ photometry and the confusion in the sdO/DO area are discussed in the following chapters.

CHAPTER 4

38 FILTER PHOTOMETRY

4.1 Introduction

A filter centred on the Balmer jump has been used with Strömgren filters in an attempt to extend the classification capabilities of the Strömgren system.

a) Behaviour of the Balmer Jump

The Balmer discontinuity or jump, caused by the merging of the higher members of the hydrogen Balmer series due to Stark broadening, is one of the major features in the spectra of early type stars. Since Stark broadening increases with surface gravity (for a general discussion see Griem (1974) and Cowley (1970)), the lines are broader and hence merge earlier in stars with higher gravity. This has been used as a major classification criterion, especially when low dispersion spectra were used, for example in the surveys of Slettebak and Stock (1959) and Slettebak and Brundage (1971).

Chalonge and Divan (1952) have presented data on the appearance of the Balmer jump for many stars. They defined two major parameters, D and λ_1. D is the difference between the Balmer and Paschen continua, while λ_1 is the wavelength at which the intensity of the spectrum is reduced to the mid-value between the levels of the continua. The parameter D was shown to be predominantly temperature dependent while λ_1 was primarily dependent on the surface gravity and hence on stellar luminosity. Thus it can be basically said that the size of the Balmer jump gives the stellar temperature while its position gives an indication of absolute magnitude.

b) The Use of Hβ Photometry

The Hβ index (Crawford, 1958) is a very good luminosity parameter for stars of spectral type A1 and earlier (see Fernie, 1965 and Crawford, 1978). For later types the β index becomes a temperature indicator. The index is a measure of the equivalent width of the Balmer line at 4861A. The value of β is determined from measurements through two filters, which have halfwidths of 150A and 30A and are both centred on the Hβ line.

Hβ photometry has been used extensively in conjunction with Strömgren photometry by Crawford and his colleagues (see Table III of Crawford, 1978). The standard system was established by Crawford and Mander (1966) and has the major advantages of being independent of atmospheric extinction and interstellar reddening. The accuracy usually attained is $\pm 0^{m}.012$ for a single observation (Crawford, 1978) and for three observations this leads to a typical error of about $0^{m}.2$ in the derived absolute magnitude. However this accuracy is better than that obtained for early type stars by other techniques. The main disadvantage is the restriction imposed by the bandpass of the narrow filter. A parameter equivalent to the β index, which could be used to the same magnitudes as uvby filters, would allow observations up to two magnitudes fainter to be made with the same telescope. This would be particularly important in faint clusters, where more extensive observation of main sequence stars could be obtained.

4.2 Choice of the Filter

The chosen filter had to cover the Balmer jump so as to give a photometric measure of the position of the discontinuity. Initially a composite glass filter made to the specification of the DDO 38 filter (McClure and Van den Burgh, 1968) was used. This filter should have had a central wavelength of 3800A and a halfwidth of 172A. However when observations obtained in 1975 with the S.A.A.O. 1m. telescope were reduced to the DDO system, a non-linear colour term was found with a discontinuity affecting early B stars. The filter was found to be positioned to the red of and wider than the DDO specification. The observations made with this filter were reduced to an independent system and showed some separation between different luminosity classes for early type stars. The resolution was smaller than hoped for and it was decided that a narrower filter would be more useful.

A halfwidth of 140A was chosen for the new interference filter, since this would give better resolution without reducing the signal below that obtained with Strömgren filters. Subdwarf B stars show Balmer lines to $H_{10} - H_{12}$, while for supergiants the last visible Balmer line may be as high as H_{29}. This led to the choice of 3775A as the central wavelength, which is roughly the position of the H_{11} Balmer line. Thus as stars with different Balmer jumps are observed, the position of the discontinuity would have a considerable effect on the measured signal.

The transmission curve of the 38 filter is shown in Fig. 4.1, along with published curves of some other filters used by different

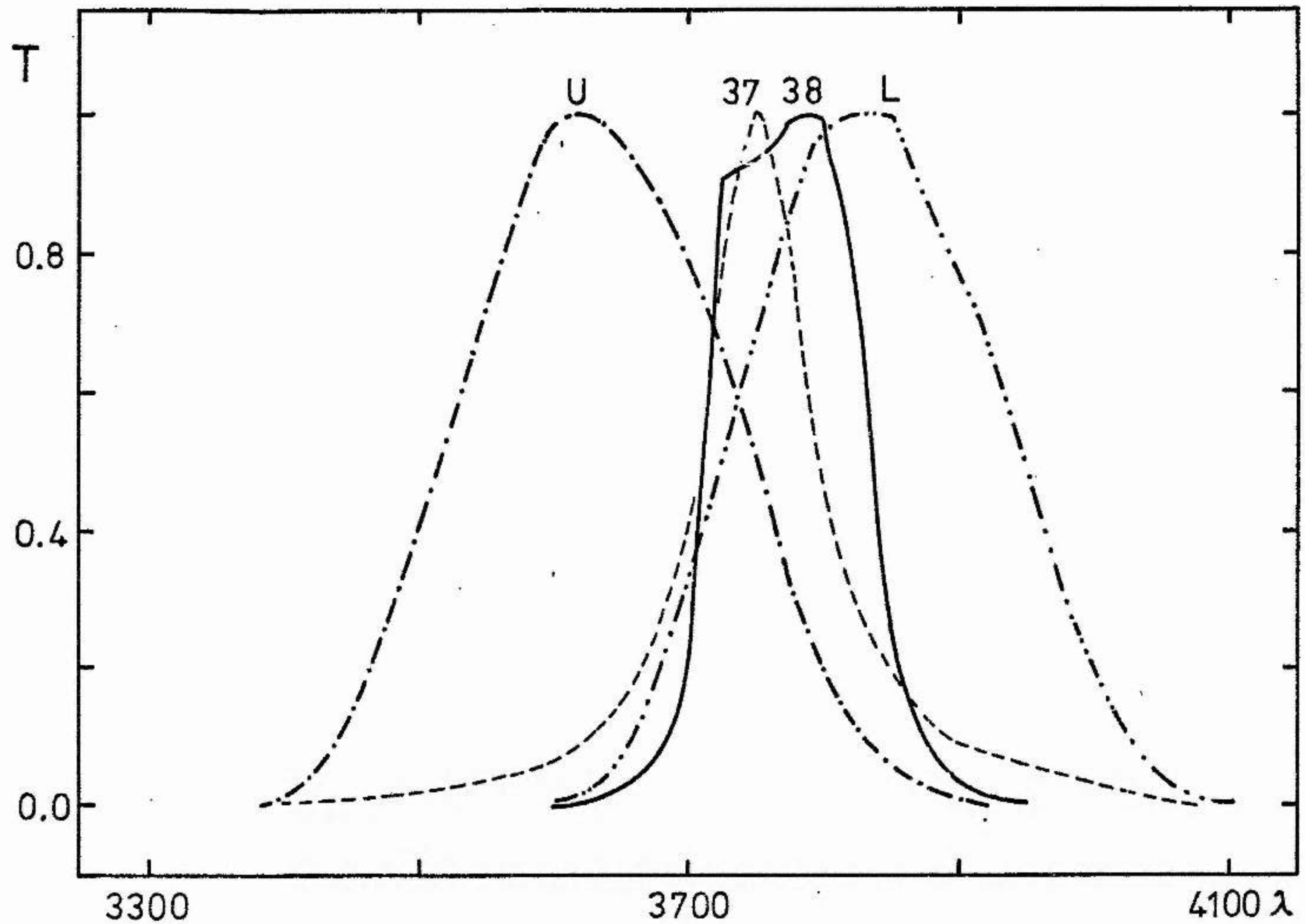


Figure 4.1 Normalised Transmission Curves for the 38 filter, the Walraven and Walraven (1960) U and L Filters and the Johnson et al. (1967) 37 Filter

photometric systems in this wavelength region. The results obtained with other photometric systems using somewhat similar filters are discussed in Section 4.8.

4.3 The 38 Observations

The 38 filter was used in conjunction with the Strömgren filters during the period 1976 August to 1977 September. The filter sequence used was ybv38u. For some of the fainter stars extra 38 observations were necessary. The Strömgren photometry obtained from these observations has been described in Section 3.2 and the observational details given are applicable here. The Strömgren standard stars were used as the basis for the 38 standard system since they were the most frequently observed stars.

In addition to standard and faint blue stars, a number of bright early type stars were observed to investigate any separation due to luminosity in the (u-38) and (38-b) colours. These stars were selected from Hoffleit (1964) with attention given to spectral type and ease of observation.

An attempt was made to use the standards observed in the previous observing run to carry the system round the sky and then tie to the stars observed initially. This would check for any errors introduced in transferring the system from one group of stars to another. Unfortunately not enough standards were available during the 1977 January/February nights and those stars observed during 1976 August and September were used as they rose. Hence the system is not tied round the sky.

4.4 Reduction Procedure

The Strömgren reduction program was adapted to reduce the colours (u-b), (38-b) and (u-38). The (u-b) colour was included as a check for comparison with the Strömgren reductions and to provide a Strömgren colour for the investigation of colour effects.

Mean extinction coefficients of 0.142 and 0.250 were initially used for (u-38) and (38-b) respectively. These values were determined by interpolation from the standard extinction coefficients normally used by the staff at S.A.A.O. (Warren, 1976). The standard star observations were reduced iteratively until self-consistent (u-38) colours were obtained. The extinction coefficients were allowed to vary after the first iteration. During the early iterations less weight was given to stars at high airmass.

The extinction coefficients and zero points derived for (u-38) and (38-b) are shown in Table 4.1. The scale factors were taken to be 1.0. The mean extinction coefficients were 0.156 ± 0.009(s.d.) and 0.226 ± 0.036(s.d.) for (u-38) and (38-b) respectively.

The residual analysis procedure described in Section 3.4 was used for the 38 photometry. Apart from time drifts, the only effects seen are in the (38-b) residuals. For ten nights with a range of standard stars a colour term existed in the (38-b) residuals when plotted against (u-b). The gradient of the colour term was 0.0089 with a standard deviation of 0.0032.

Table 4.1 Extinction Coefficients and Zero Points for (u-38) and (38-b)

		(u-38)		(38-b)	
	Telescope	Extinction	Zero Point	Extinction	Zero Point
76 Aug 12/13	1m.	0.159	0.703	0.230	-0.023
76 Aug 20/21	0.5m.	0.148	0.647	0.188	-0.068
76 Aug 23/24	0.5m.	0.150	0.651	0.254	0.012
76 Sept 3/4	1m.	0.160	0.695	0.255	0.004
76 Sept 6/7	1m.	0.155	0.677	0.226	-0.045
76 Nov 1/2	1.9m.	0.173	0.627	0.147	-0.203
76 Nov 6/7	1.9m.	0.148	0.592	0.276	-0.074
76 Nov 9/10	1.9m.	0.169	0.628	0.230	-0.113
77 Feb 2/3	1m.	0.157	0.618	0.204	-0.025
77 May 10/11	0.5m.	0.153	0.443	0.205	-0.016
77 Sept 21/22	1m.	0.144	0.430	0.263	0.098
77 Sept 22/23	1m.	0.161	0.435	0.239	0.076

4.5 Results

The (u-38) and (38-b) colours derived for the standard stars and the selection of bright stars are listed in Tables 4.2 and 4.3 respectively. The tables contain the star name taken from Hoffleit (1964), an MK classification, the (u-38) and (38-b) values (with their mean errors in the case of the standard stars), the number of observations and an Hβ index from Lindemann and Hauck (1973), if available. The mean errors were calculated as

$$\left[\sum (\text{residual})^2/(n-1) \right]^{1/2}$$

The MK classifications were taken from the compilations of Jaschek et al. (1966), Kennedy and Buscombe (1974) and Buscombe (1977). In fact a majority of the classifications are from Hiltner, Garrison and Schild (1969).

Table 4.4 gives the (u-38) and (38-b) colours for a sample of faint blue stars. The spectral types were determined from Strömgren observations by Kilkenny, Hill and Brown (1977) and the observations in Chapter 3. However in the cases of LB 3384, BD-9°4395, BD-1°3438 and BD+13°3224 the spectral types are from spectroscopic classifications. The sources of the spectral classifications are given in Section 3.5 except in the case of BD+13°3224 which is discussed in Section 6.3.

From ninety five observations of the forty three stars in Tables 4.3 and 4.4 with more than one observation, the standard deviations in a single observation were found to be ±0.016 and ±0.019 in (u-38) and (38-b) respectively. For stars having colours with standard deviation of more than twice the standard deviation in a single observation the value is followed by a colon. These errors

Table 4.2 (u-38) and (38-b) Colours for Standard Stars

Star	MK Class	(u-38)	m.e.	(38-b)	m.e.	n	β
HR 531	F2IV	0.109	0.011	1.323	0.011	7	2.738
HR 875	A1V	0.259	0.004	1.236	0.007	12	
HR 1089	G0	0.107	0.008	1.533	0.010	3	2.619
HR 1258	B2.5V	-0.266	0.003	0.476	0.009	7	2.654
HR 1861	B1V	-0.347	0.004	0.343	0.007	10	2.612
HR 3849	B5V	-0.131	0.007	0.618	0.018	4	2.700
HR 5530	F4IV	0.042	0.003	1.295	0.003	4	2.678
HR 5660	F0I	0.738	0.004	1.389	0.011	3	2.743
HR 6141	B2V	-0.251	0.008	0.534	0.003	9	2.662
HR 6595	F6V	0.010	0.005	1.314	0.005	6	2.648
HR 6930	A3V	0.392	0.005	1.200	0.005	4	2.842
HR 7446	B0.5III	-0.296	0.005	0.399	0.006	9	2.565
HR 7610	A1V	0.171	0.004	1.201	0.006	3	2.912
HR 7773	B9V	0.212	0.003	1.035	0.005	10	2.856
HR 8060	A3m?	0.171	0.005	1.333	0.009	6	2.859
HR 8551	K0III-IV	-0.010	0.002	1.476	0.001	3	
HR 8826	A2V	0.310	0.008	1.254	0.004	7	2.822
HR 9006	B3V	-0.216	0.004	0.537	0.006	8	2.675
HR 9091	B5V	-0.111	0.006	0.648	0.004	9	2.704

Table 4.3 (u-38) and (38-b) Colours for Bright Stars

Star	MK Class	(u-38)	(38-b)	n	β
HR 1292	F4V	0.092	1.344	1	2.706
HR 2056	B5V	-0.163	0.640	1	2.717
HR 2501	B2III	-0.331	0.383	1	2.584
HR 2590	F2III	0.145	1.270	1	2.699
HR 2595	B2III	-0.193	0.387	2	2.589
HR 2614	B2.5III	-0.264	0.418	2	2.644
HR 2678	B0.5III	-0.290	0.458	1	2.585
HR 2679	O7.5V	-0.396	0.341	1	2.598
HR 2699	B1II	-0.250	0.499	1	2.587
HR 2707	A8V	0.257	1.353	1	2.743
HR 2739	O9II-III	-0.387	0.316	1	2.602
HR 2928	B2III	-0.311	0.385	2	2.620
HR 2961	B2.5V	-0.173	0.535	1	2.662
HR 3001	B9V	-0.076	0.693	2	2.740
HR 3004	B1.5III	-0.293	0.351	2	2.600
HR 3035	B2.5III	-0.118	0.538	2	2.640
HR 3219	O9.7Ib	-0.330	0.404	2	2.556
HR 3293	B1.5III	-0.248	0.451	1	2.586
HR 3294	B1.5III	-0.287	0.395	2	2.613
HR 3456	B6Ia	0.016	0.683	2	2.548
HR 3459	G2Ib	0.141	1.954	1	2.595
HR 3494	B4Ia	-0.064:	0.695	2	2.561
HR 3878	B0.5III	-0.329	0.325	1	2.553

Star	MK Class	(u-38)	(38-b)	n	β
HR 3898	B7III	0.104	0.681	1	
HR 4119	B6V	-0.114	0.695	1	2.730
HR 4695	K1III	0.050	2.856	1	
HR 4908	O9Ia	-0.343	0.416	1	2.543
HR 5011	G0V	0.011	1.676:	2	2.594
HR 5026	B5III	-0.125	0.704	1	2.721
HR 5030	B8V	0.021	0.881	1	2.725
HR 5059	A7III	0.225	1.343	2	2.845
HR 5270	G0VI	0.297	1.683	2	2.540
HR 5915	B5V	-0.131	0.731	1	2.690
HR 5934	B3V	-0.139	0.803	1	2.721
HR 6164	O9Ia	-0.213	0.744	1	2.516
HR 6167	B8V	0.018	0.767	1	2.734
HR 6214	B3V	-0.199	0.618	1	2.680
HR 6219	B0Iab	-0.349	0.346	2	2.554
HR 6788	B2III	-0.281	0.394	1	2.596
HR 7257	B5V	-0.012	0.694	1	2.693
HR 7316	B3V	-0.089	0.610	1	2.678
HR 7527	B5V	-0.093	0.643	1	2.702
HR 7560	F8V	0.012	1.482	2	
HR 9049	B6V	-0.058	0.748	2	2.738

Table 4.4 (u-38) and (38-b) Colours for Faint Blue Stars

Star	(u-38)	(38-b)	n	Type
JL 163	-0.029	1.357	1	Late F
LB 3130	0.228	1.124	1	Ahb
LB 3134	0.450	1.173	1	Ahb
JL 198	0.005	1.367	1	F6
LB 3162	0.169	1.303	1	Early F
PHL 6807	0.495	1.248	3	Ahb
LB 3176	0.482	1.184	2	Ahb
LB 1591	0.341	1.143	1	Ahb
TS 192	-0.394	0.357	1	sdB
TS 195	-0.213	0.577	3	B3(sd?)
PHL 3368	0.172	1.351	1	A1
PHL 8374	0.408	1.133	1	Ahb
PHL 1434	-0.303	0.563	2	B2(sd?)
LB 3286	0.165	1.232	1	sdFG
LB 1652	0.322	0.995	1	A0
PHL 8667	-0.013:	1.419:	2	Late F
PHL 1548	-0.442	0.237	1	sdO,DO
TS 401	-0.063	0.653	1	B6
LB 3384	-0.259:	0.448:	2	B1.5Ia
HD 96008	0.155	1.305	2	Late A(m?)
CD-80° 540	0.166	1.526	1	Late A
CD-72° 1184	-0.347	0.373	1	B0III
CD-80° 656	0.235	1.600	1	Am?
BD-17° 3883	0.393	1.159	4	Ahb

Star	(u-38)	(38-b)	n	Type
Abell 36	-0.476	0.086	1	sdO,DO
BD-2°3766	-0.323	0.400	1	B1
HD 125924	-0.324	0.423	1	B1.5(B2IV)
HD 127493	-0.447	0.123	3	sdO
HD 130095	0.425	1.170	1	Ahb
HD 139961	0.445	1.241	3	Ahb
HD 149382	-0.435	0.209	1	sdB
BD-9°4395	-0.274	0.456	2	He-rich B star
HD 150055	0.293	1.323:	3	B9.5
BD+13°3224	-0.226	0.388	1	He-rich B giant
BD-1°3438	0.088	0.997	2	He-rich B star
LB 3119	0.359	1.097	1	Ahb
JL 22	-0.297	-0.027	1	sdO,DO
JL 25	-0.451	0.163	1	sdB,DB
JL 36	-0.351	0.448	1	B1
JL 62	-0.074	0.590	1	B5
PHL 1580	-0.313	0.306	1	B1
PHL 44	-0.399	0.359	1	B0.5(sd?)
PHL 48	-0.360	0.452	1	B2
PHL 4748	0.303	1.015	1	Ahb
PHL 110	0.204	0.860	1	B9
LB 10000	0.022	1.449	2	F(sd?)
JL 87	-0.362	0.417	1	B0(sd?)
PHL 159	-0.282	0.451	2	B1.5
PHL 178	-0.454	0.074	1	sdO,DO
PHL 227	-0.295	0.569	1	B1
LB 1502	0.168	0.794	1	B9

Star	(u-38)	(38-b)	n	Type
PHL 1957	0.338	0.873	1	B9.5(hb?)
PHL 334	-0.460	0.209	2	sdB
PHL 5382	-0.028	0.749	1	B7
PHL 375	-0.034	0.865	1	Late B
LB 1514	0.350	1.087	1	Ahb
JL 124	-0.319	0.534	1	sdB
JL 129	-0.446	0.692	1	DA
PHL 460	-0.153	0.654	2	B5
PHL 5882	0.200	1.377	2	A(m?)
PHL 2408	0.460	1.155	1	Ahb
LB 1529	0.445:	1.226	2	Ahb
LB 1538	0.444	1.207	1	Ahb
PHL 610	-0.442	0.257	1	sdB,DB
BD-13° 842	-0.453	0.230:	3	sdOp,DOp
CD-31° 4800	-0.442:	0.083	2	sdO,DO
BD-3° 2179	-0.447	0.107:	2	sdO,DO
HD 76431	-0.435	0.271	1	sdB
0904-02	0.212	1.381	1	Early A
HD 171858	-0.412	0.357	2	sdB
HD 188112	-0.387	0.533	2	B1.5(sdB?)
CD-35° 15910	-0.436	0.325	2	sdB
HD 137518	-0.139	0.592	2	Binary
HD 138503	-0.254	0.529	2	Binary

may be slightly overestimated since stars known to be variable in Strömgren photometry were included in the analysis.

4.6 The Behaviour of the (u-38) and (38-b) Colours

The (u-38) and (38-b) colours are plotted against the reddening-free parameter [u-b] in Figs. 4.2 and 4.3 for the standard and bright stars. The definition

$$[u-b] = (u-b) - 1.54(b-y)$$

was used (Crawford, 1978). [u-b] is temperature dependent for B stars and hence these diagrams show the relationships between the colours and temperature. Similar diagrams for the faint blue stars are shown as overlays to Figs. 4.2 and 4.3. The error bars in these and the following diagrams indicate the error expected for a single observation.

For main sequence stars the (u-38) colours increase to a maximum at spectral type A3 and then decrease for cooler stars. The overall behaviour is roughly linear as shown in the inset to Fig. 4.2. Some separation according to luminosity is seen with main sequence stars having systematically smaller values than giants. This may be partly due to reddening which moves stars vertically in both diagrams. Although main sequence stars still tend to have lower (u-38) values, confusion occurs between dwarfs and giants earlier than B2 but this may be partly caused by errors in the MK classification. O and B0 giants and supergiants occupy the same region. Subdwarfs have smaller (u-38) colours than stars with lower surface gravity. Thus (u-38) is not only strongly temperature

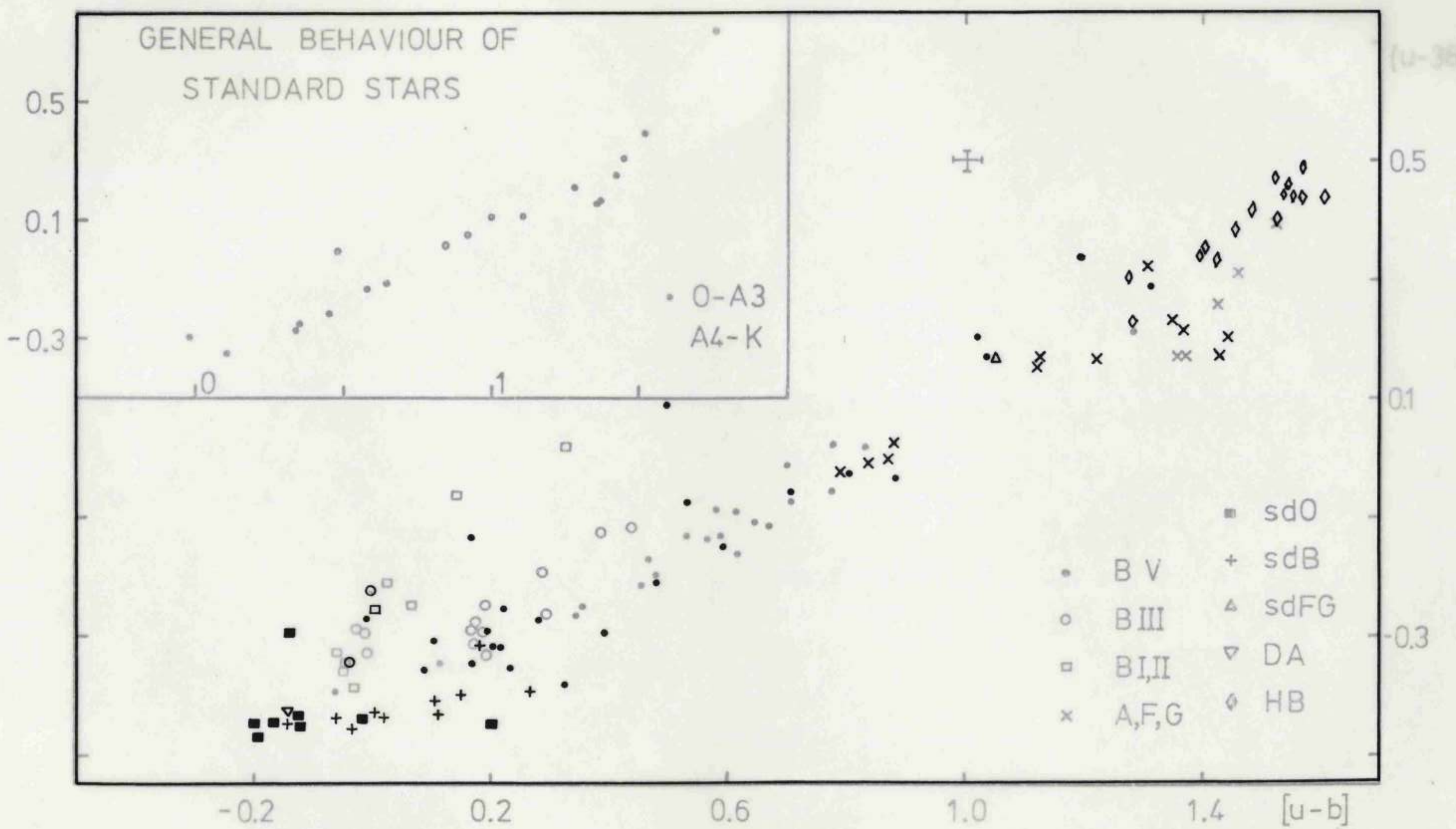


Figure 4.2 (u-38) - [u-b] Diagram for Bright Stars with Overlay showing Faint Blue Stars

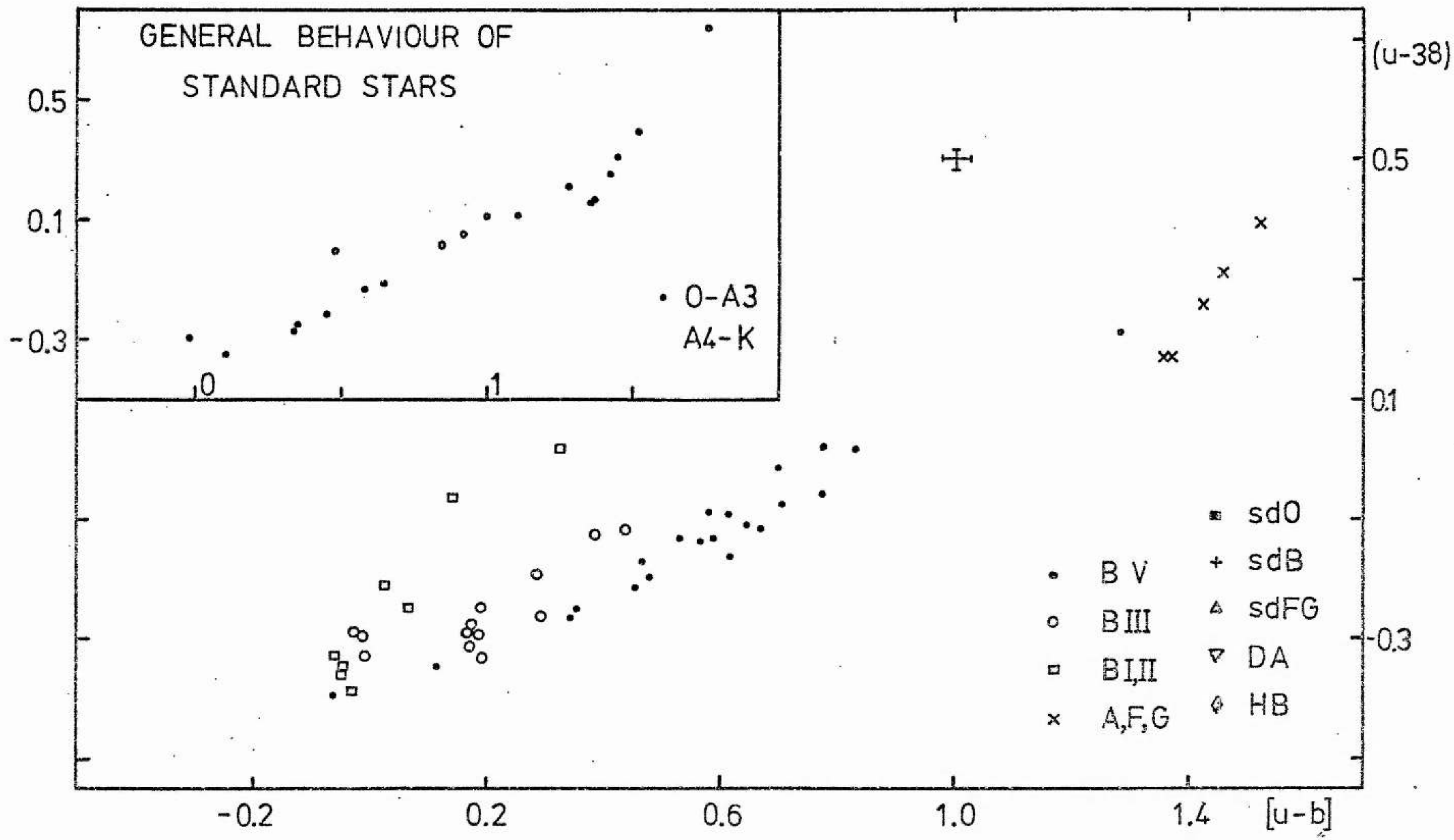


Figure 4.2 (u-38) - [u-b] Diagram for Bright Stars with Overlay showing Faint Blue Stars

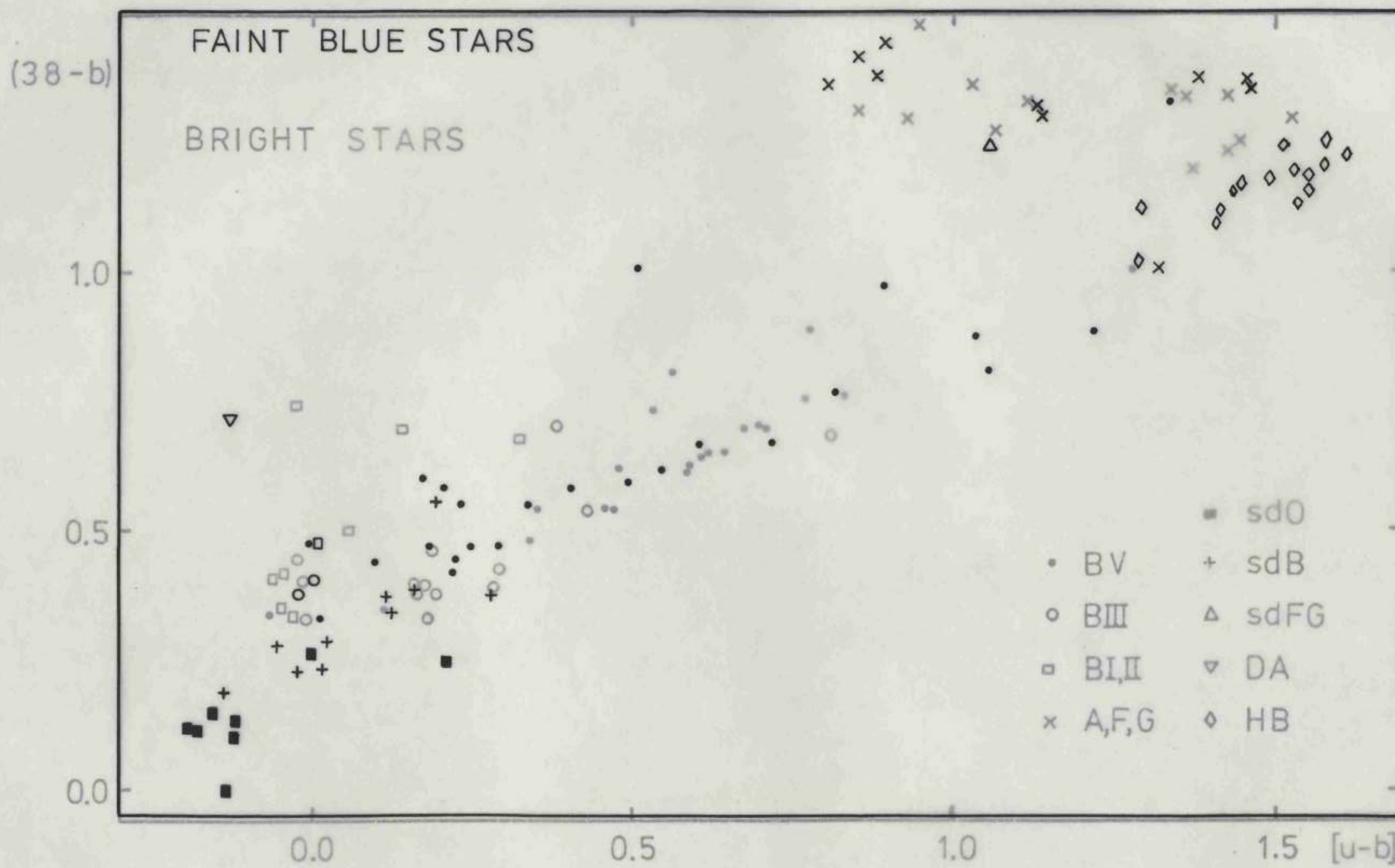


Figure 4.3 (38-b) - [u-b] Diagram for Bright Stars with Overlay showing Faint Blue Stars

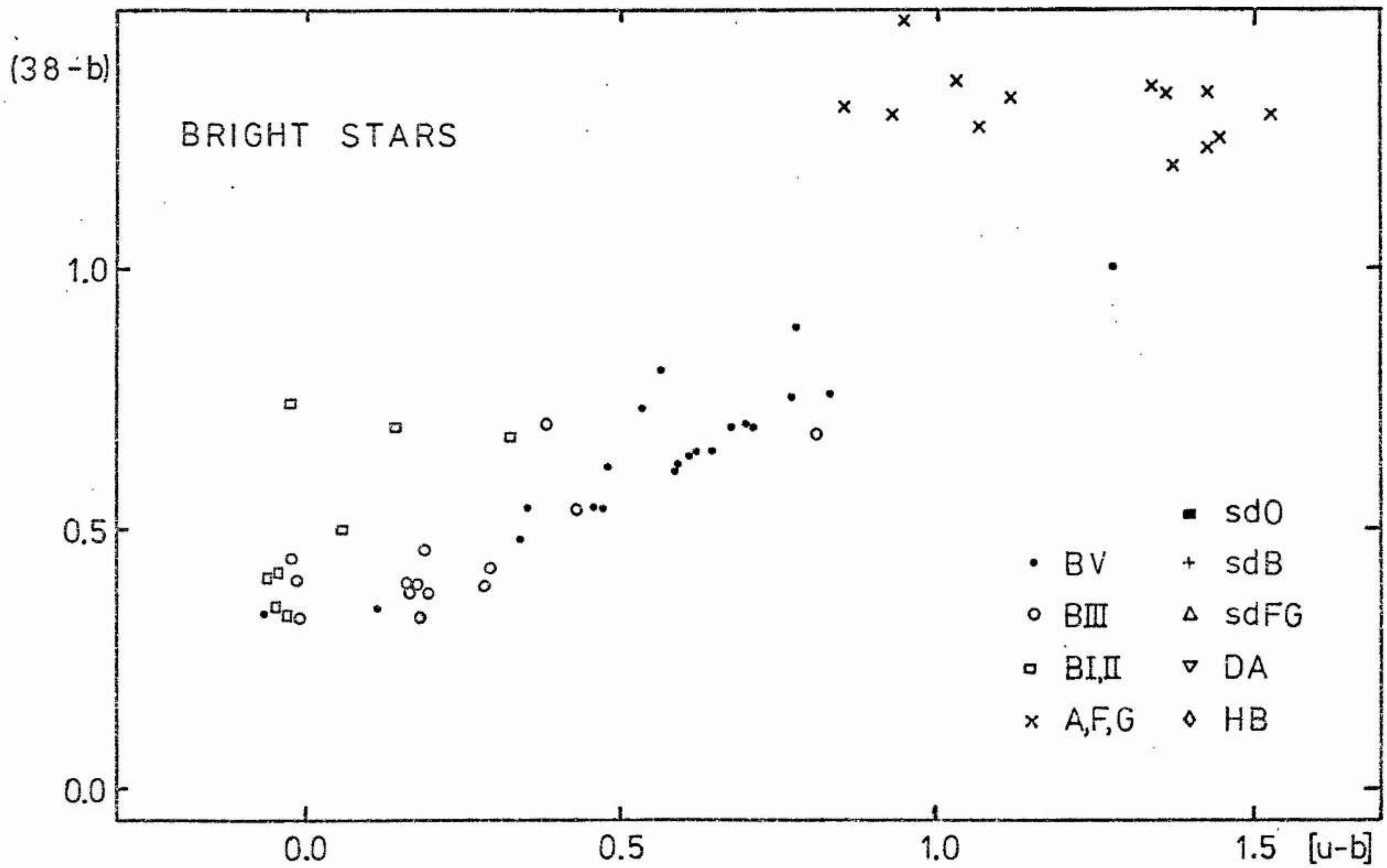


Figure 4.3 (38-b) - [u-b] Diagram for Bright Stars with Overlay showing Faint Blue Stars

dependent for O, B and early A stars but also has a noticeable, if slight, surface gravity effect.

(38-b) increases continuously from the hottest to the coolest stars. The colour is strongly dependent on temperature for B stars and there is no obvious separation between luminosity classes. Many of the stars are probably affected by reddening which is much greater in (38-b) than (u-38). Dwarfs and subdwarfs form a continuous sequence but the single DA star is isolated from other stars.

The behaviour of the colours with H_β index is shown in Fig. 4.4. Crosses represent A and F stars while B stars are shown by dots. The symbols for giants are circled and those for supergiants are enclosed by squares. The relationship between (38-b) and β is well defined for both B and AF stars. However the effect of interstellar reddening is to spread the points in the positive (38-b) direction. (u-38) is poorly correlated with β . The B stars lie in a broad band while the A and F stars show no systematic relationship.

4.7 Reddening-free Colours [u-38] and [38-b]

Colours independent of interstellar extinction, [u-38] and [38-b], were evaluated using the Whitford (1958) extinction curve. From this curve Golay (1974) gives $E(35-38)/E_{B-V} = 0.306$ for the DDO (35-38) colour, which is equivalent to $E(35-38)/E(b-y) = 0.414$. Since the DDO 35 filter is in practice the same as the Strömgren u filter and the DDO 38 filter is positioned only slightly to the red of the 38 filter discussed in this work, $E(u-38)/E(b-y)$ was taken to be 0.41. Using $E(u-b)/E(b-y) = 1.54$, $E(38-b)/E(b-y)$ is found to be 1.13.

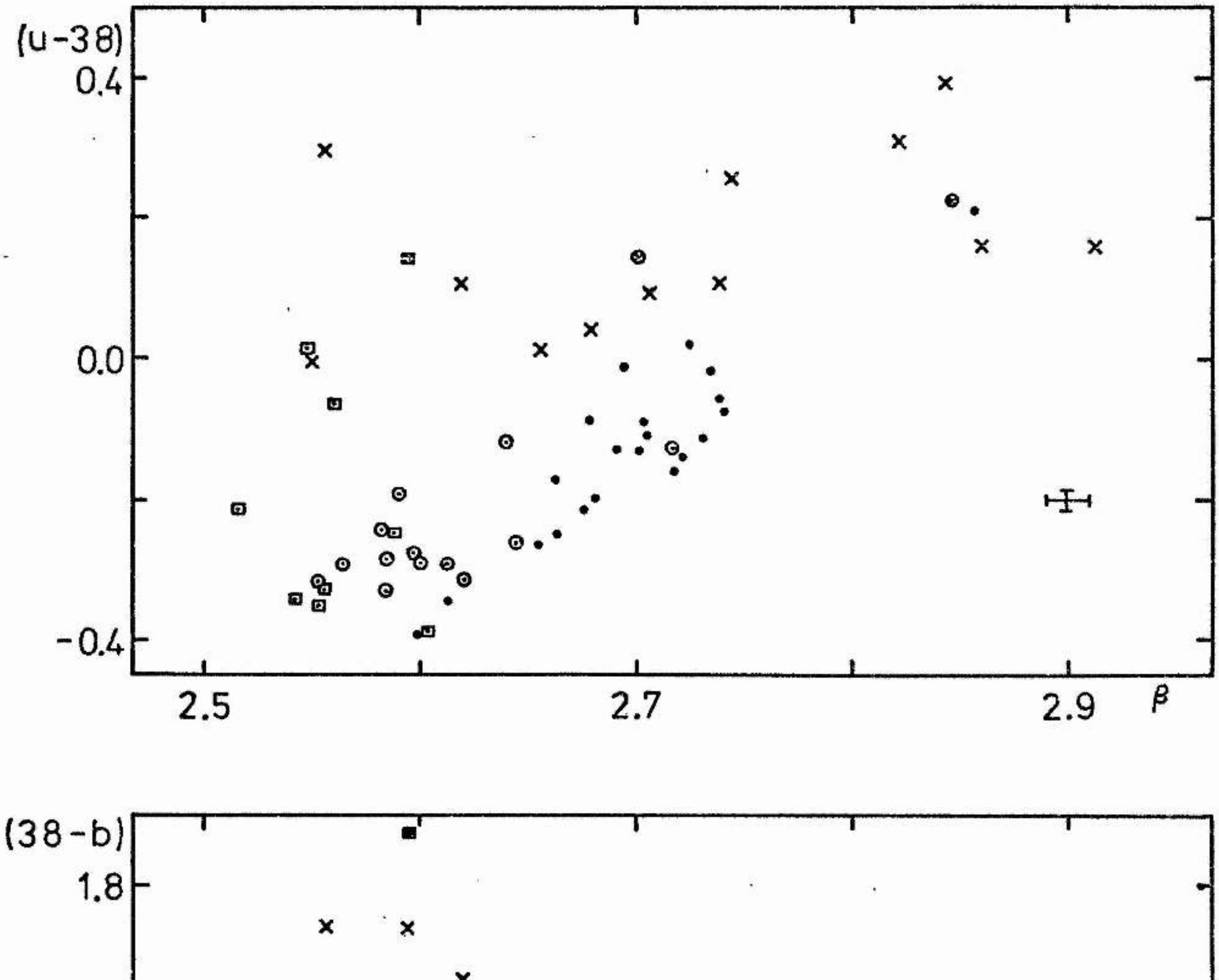


Figure 4.4 The (u-38) - β and (38-b) - β Diagrams

• - B stars x - AF stars o - giants ◻ - supergiants

The values can only be considered approximate and a better determination could be obtained from the study of a sample of reddened O stars.

The [u-38] and [38-b] colours were calculated from

$$[u-38] = (u-38) - 0.41(b-y)$$

and

$$[38-b] = (38-b) - 1.13(b-y)$$

The [u-38] - [u-b] and [38-b] - [u-b] diagrams are shown in Figs. 4.5 and 4.6 respectively, with the faint blue stars on overlays. The [u-38] index behaves linearly with [u-b] for B dwarfs. For stars later than B1 all luminosity classes show a good degree of separation. A and F stars occur below the B stars as [u-b] decreases with temperature. The [38-b] index is also linearly dependent on [u-b] for B stars but in this case stars of all luminosity classes lie along the line. Two giants, HR 5026 (B5III) and HR 3898 (B7III), lie off the line. Stars later than A2 are positioned above the B star locus. The star JL 22 shows peculiar colours when compared with other sdO stars.

Plots of [u-38] and [38-b] against Hβ index are shown in Figs. 4.7 and 4.8. The symbols are as in Fig. 4.4. [u-38] is poorly correlated with β. The B stars show a spread of about $0^m.15$ in [u-38] for any given value of β. A and F stars show a random arrangement. However very good agreement is found between [38-b] and β. The relation for B stars is linear with very small scatter except among the hottest stars. A linear relation may also exist for A and F stars but not enough data are available to be certain.

With [38-b] as the dependent variable least squares fits

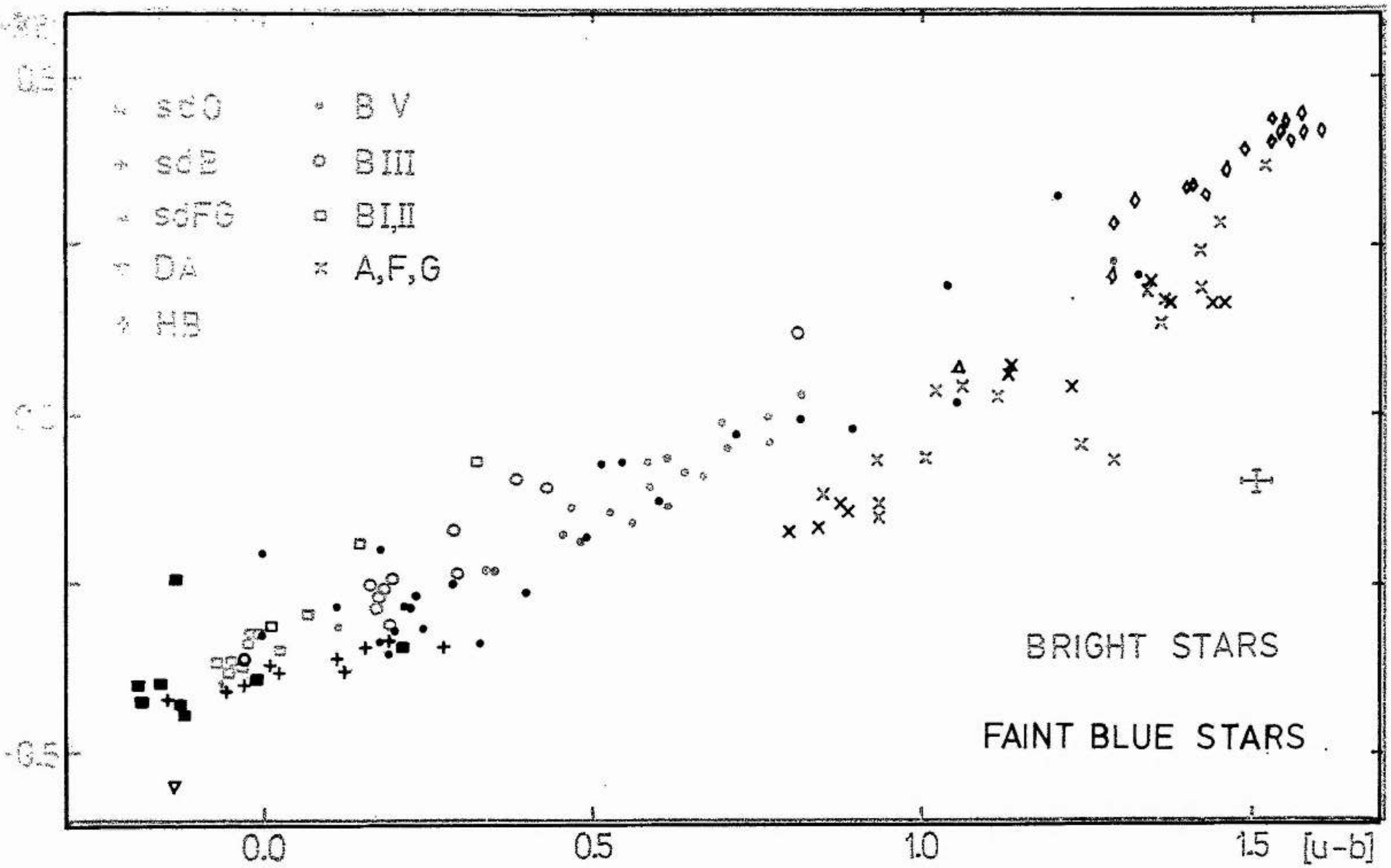
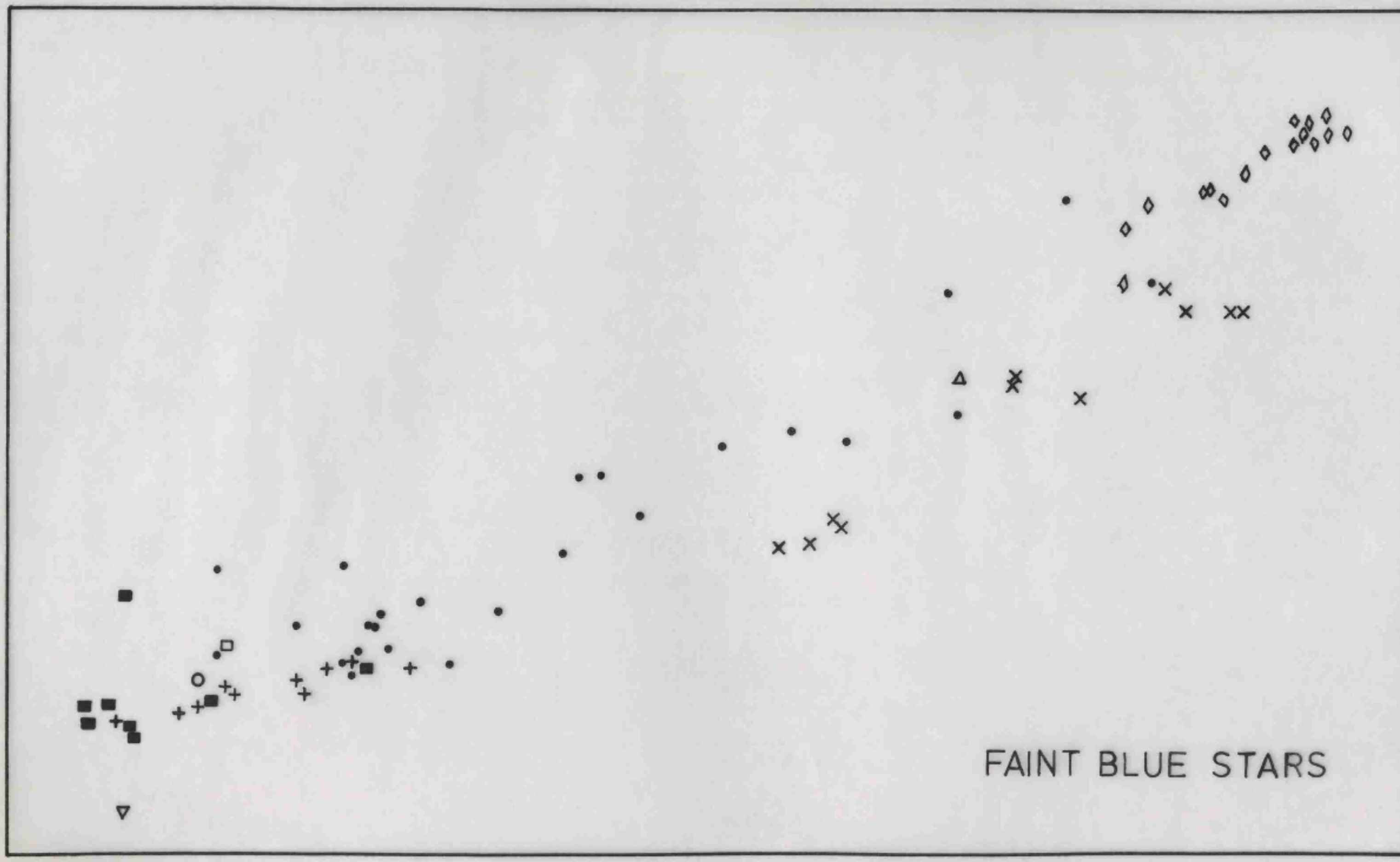


Figure 4.5 [u-38] - [u-b] Diagram for Bright Stars with Overlay showing Faint Blue Stars


FAINT BLUE STARS

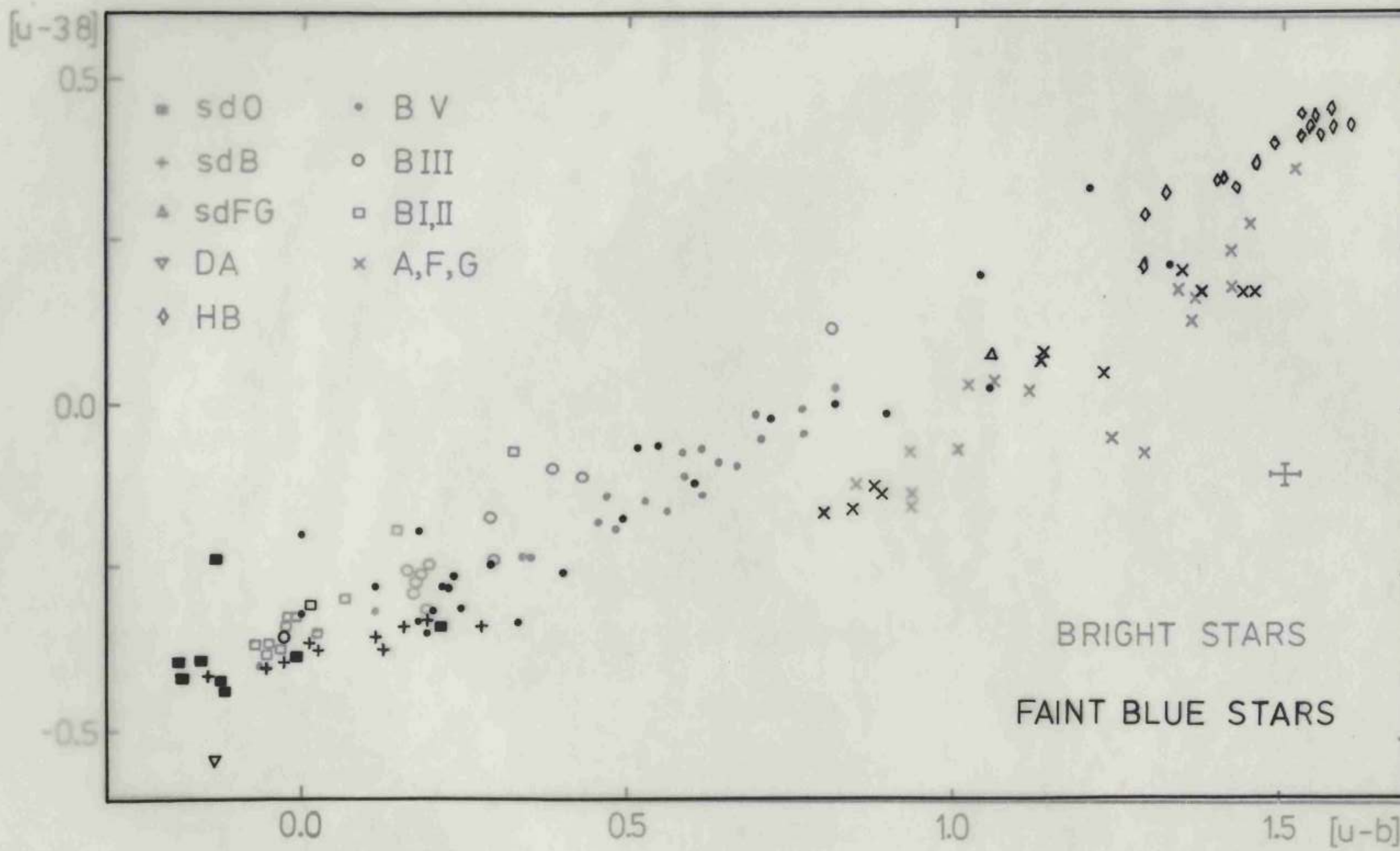


Figure 4.5 [u-38] - [u-b] Diagram for Bright Stars with Overlay showing Faint Blue Stars

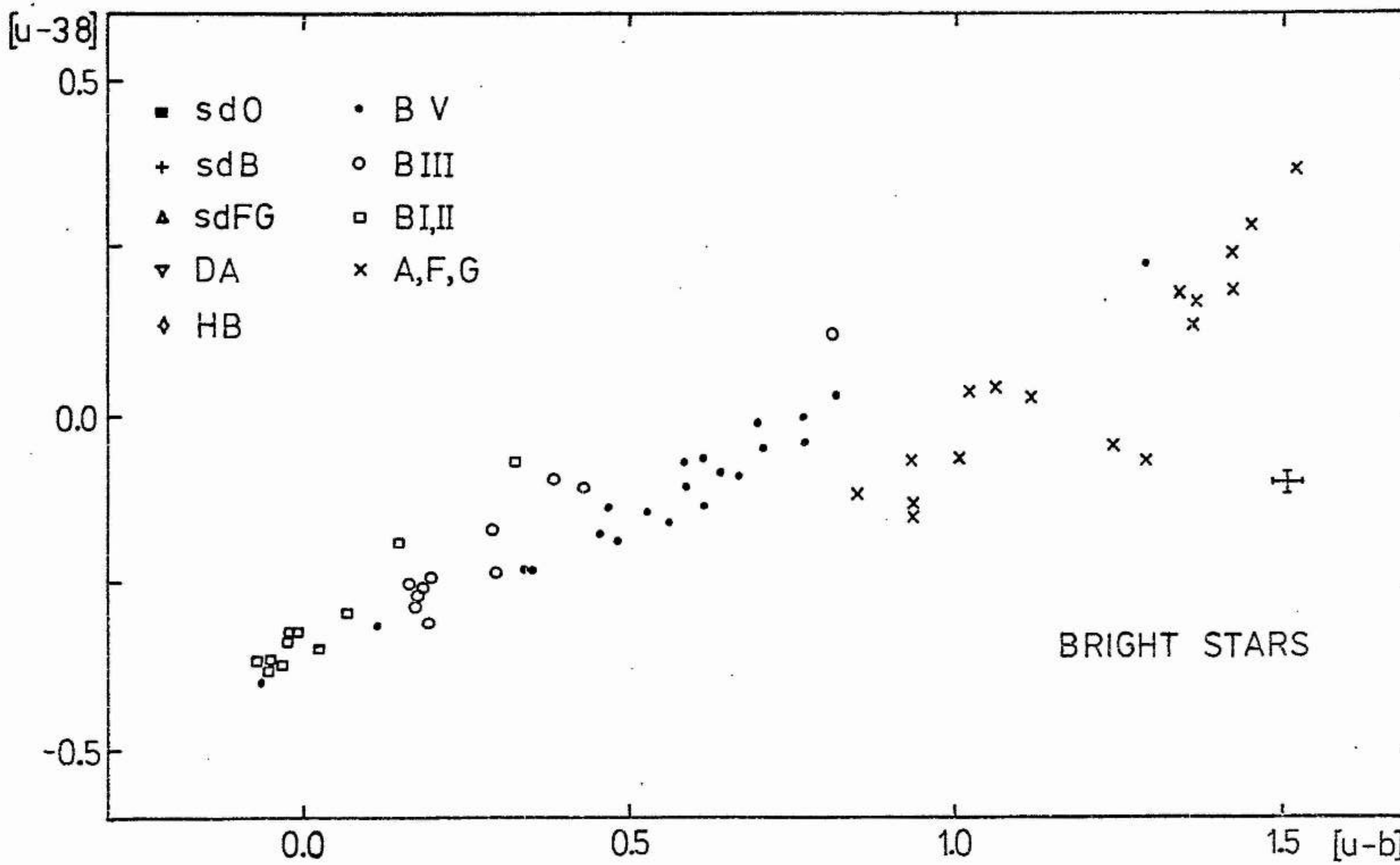
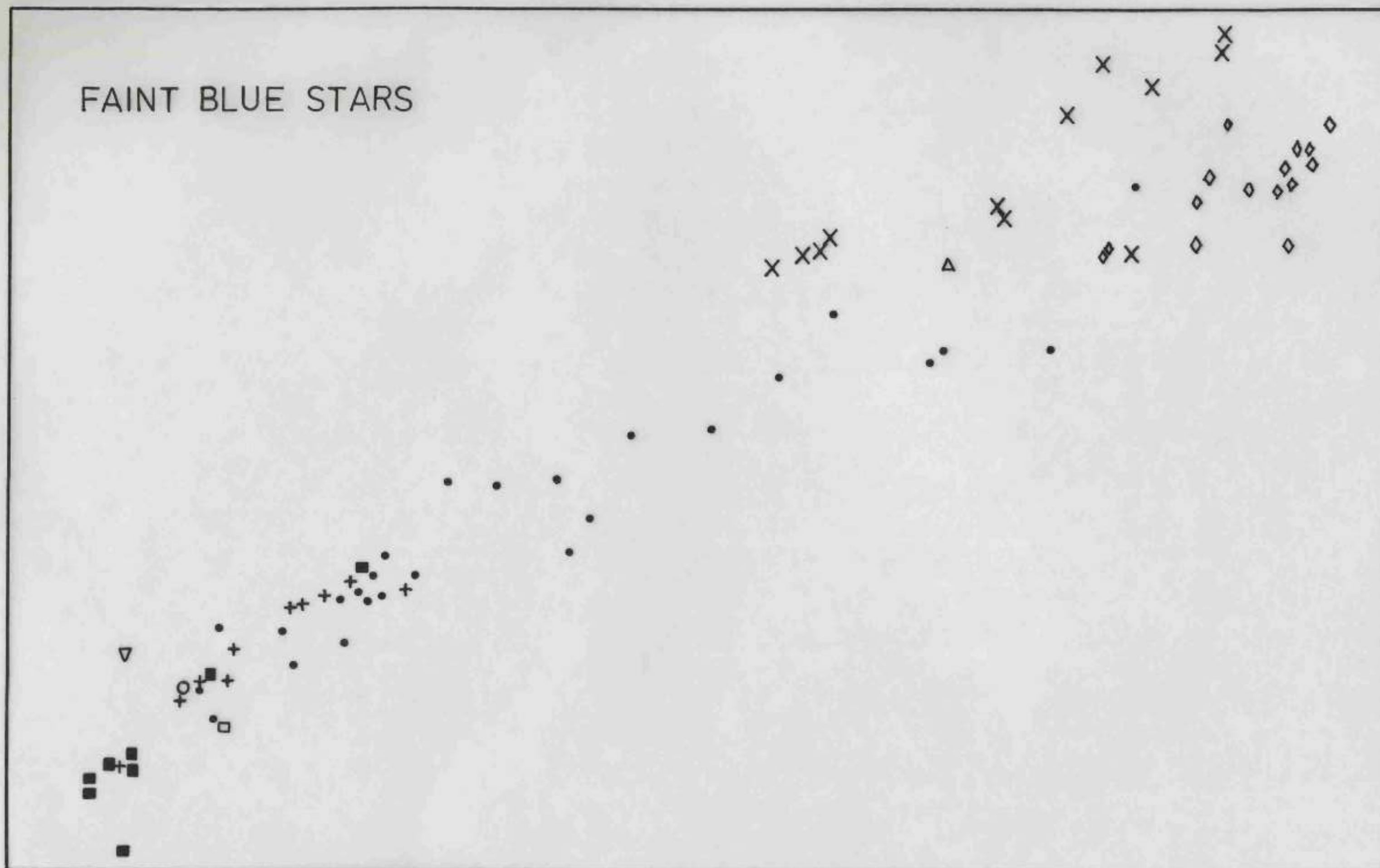


Figure 4.5 [u-38] - [u-b] Diagram for Bright Stars with Overlay showing Faint Blue Stars


FAINT BLUE STARS

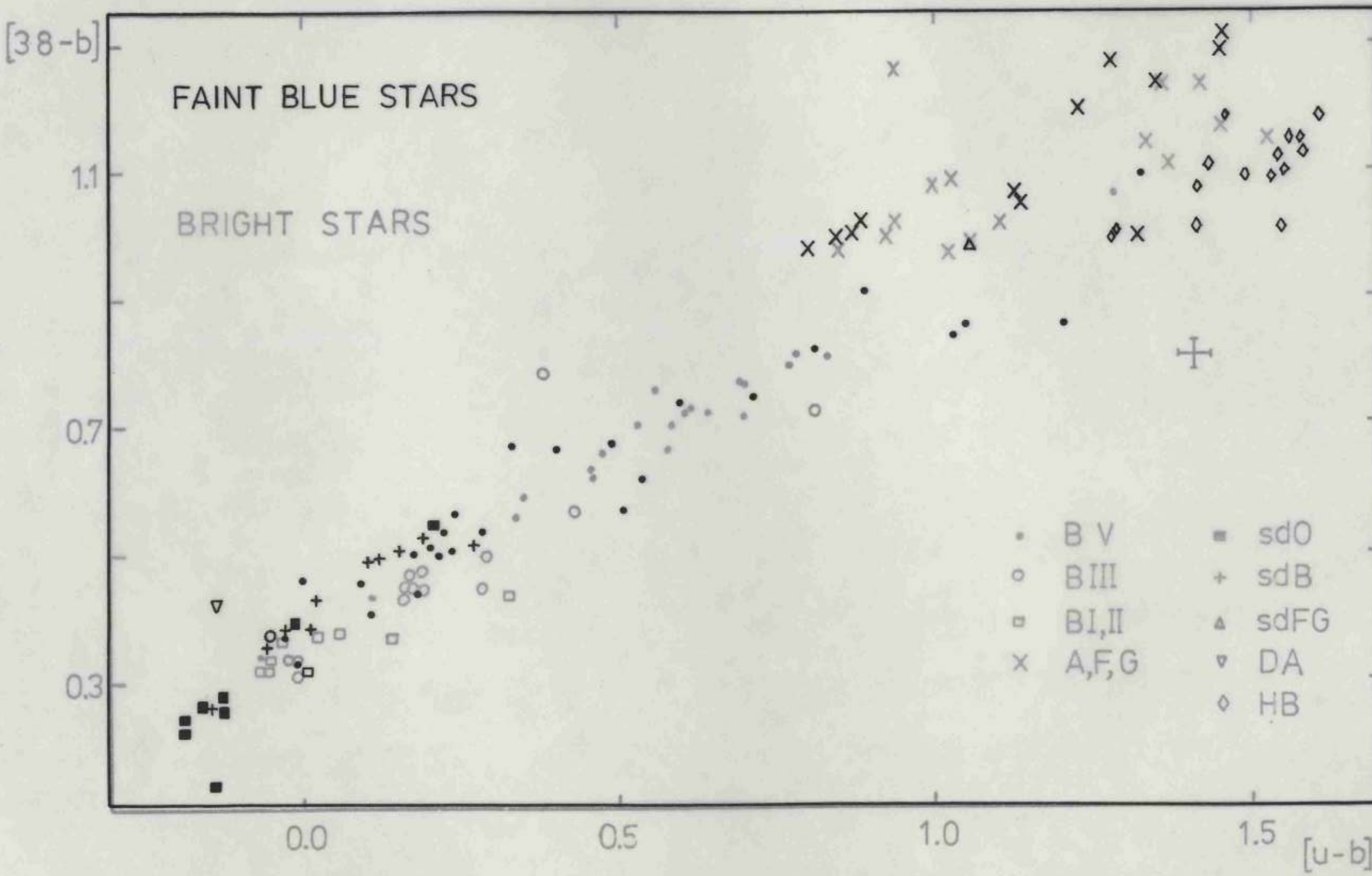


Figure 4.6 [38-b] - [u-b] Diagram for Bright Stars with Overlay showing Faint Blue Stars

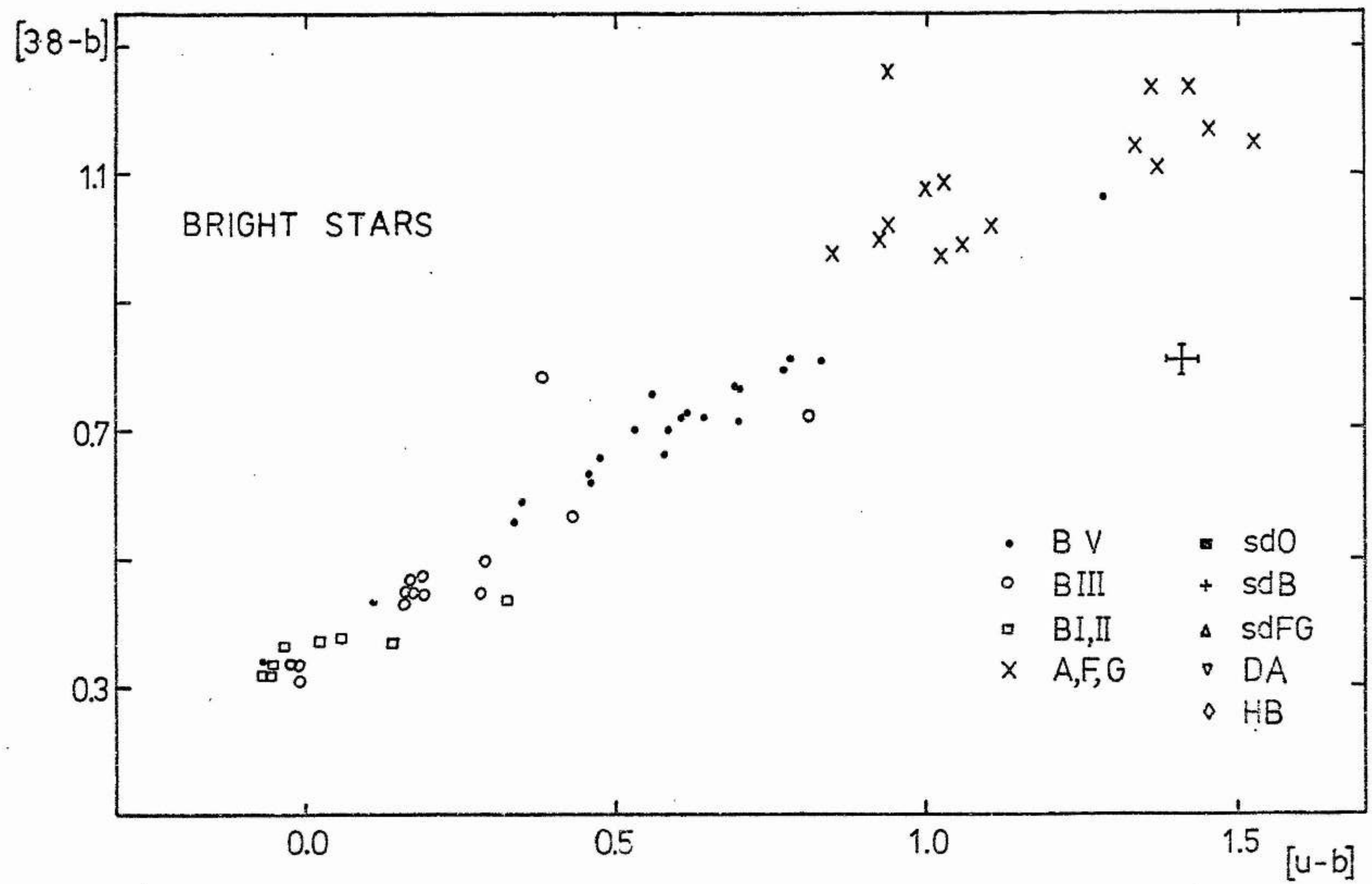


Figure 4.6 [38-b] - [u-b] Diagram for Bright Stars with Overlay showing Faint Blue Stars

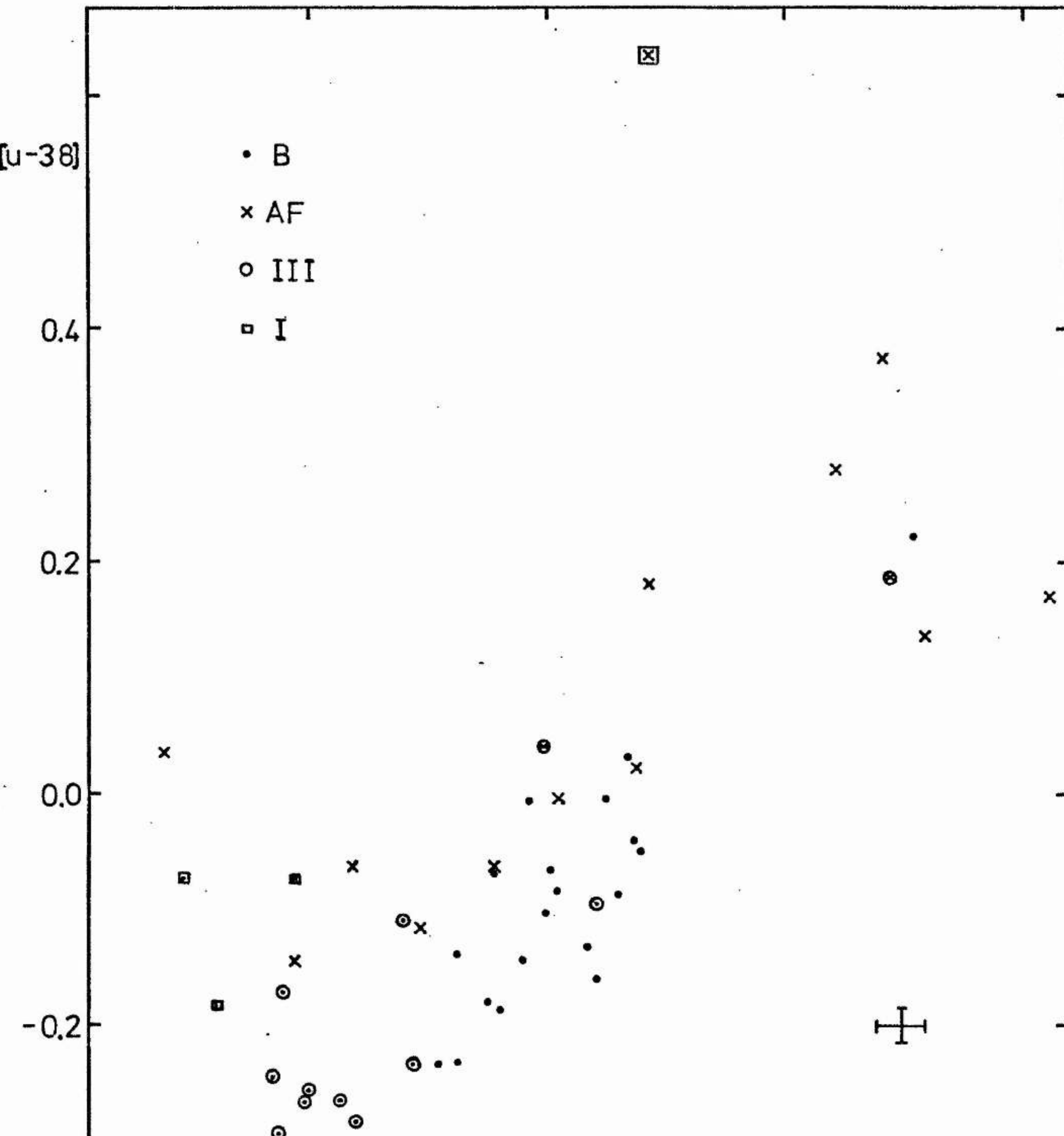


Figure 4.7 [u-38] as a Function of the Hβ Index

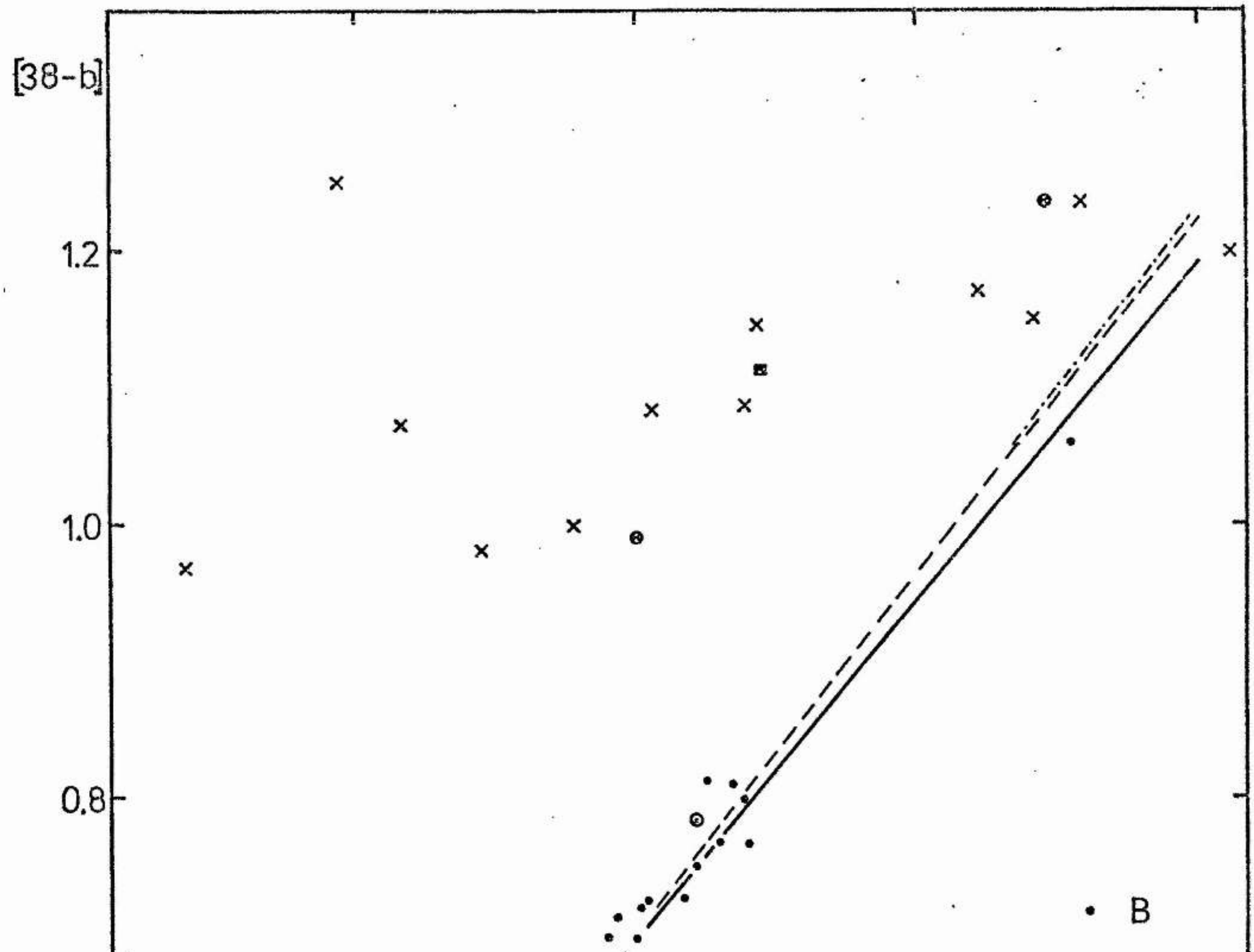


Figure 4.8 [38-b] as a Function of the Hβ Index

for the B star data give

$$\beta = (0.359 \pm 0.017)[38-b] + (2.450 \pm 0.012) \quad \text{for dwarfs,}$$

$$\beta = (0.367 \pm 0.013)[38-b] + (2.443 \pm 0.008) \quad \text{for dwarfs and giants}$$

and $$\beta = (0.383 \pm 0.015)[38-b] + (2.431 \pm 0.009) \quad \text{for luminosity classes I-V.}$$

4.8 Comparison with Similar Filters in Other Systems

A filter centred in the 3600 - 4000A region has been used in several photometric systems. Some of these filters are now discussed and compared with our 38 filter. The transmission curves for some of the filters are shown in Fig. 4.1.

a) The Walraven System

This system, designed by Walraven and Walraven (1960), has a filter (L) positioned at 3900A with a halfwidth of 140A and also contains two filters which are somewhat similar in position to the Strömgren u and b filters. These filters are U at 3670A with a halfwidth of 260A and B at 4295A with a halfwidth of 420A.

Walraven and Walraven show a correlation between [B-L] and the Hβ index (see their Fig. 5) which is curved, whereas the relation between [38-b] and β shown in Fig. 4.8 is linear. They also give a [B-L] - [B-U] diagram which shows separation between supergiants and other stars. However B dwarfs and giants are not separated. Lub and Pel (1977) have described the present state of the Walraven system and stress its application to stars of type A-G.

Comparisons of (L-B) with (38-b) and (U-L) with (u-38) for stars observed in both systems are shown in Fig. 4.9. (38-b) correlates well with (L-B) while the scatter in the (U-L) - (u-38) diagram is greater. This is to be expected since the U filter also covers the Balmer jump region and the L filter contains a smaller proportion of overlapping to free Balmer lines. The least squares fits to the data give

$$(L-B) = (-0.224 \pm 0.006)(38-b) + (0.099 \pm 0.007)$$

and

$$(U-L) = (-0.462 \pm 0.039)(u-38) - (0.126 \pm 0.011).$$

b) The Johnson 13-Colour System

Johnson, Mitchell and Latham (1967) describe the blue filters of this system which include 35 (at 3530A with a halfwidth of 100A), 37 (at 3750A with a halfwidth of 100A) and 45 (at 4590A with a halfwidth of 230A). Good agreement is found between the Johnson (37-45) and (35-37) colours and the (38-b) and (u-38) colours as shown in Fig. 4.10. Linear least squares fits, excluding HR 8551 in the (37-45) - (38-b) diagram, give

$$(37-45) = (0.891 \pm 0.019)(38-b) - (1.030 \pm 0.025)$$

and

$$(35-37) = (0.878 \pm 0.046)(u-38) - (0.241 \pm 0.009).$$

Again the agreement is best for (38-b) suggesting that even a small difference in filter position affects comparison with the (u-38) colour. The largest residuals in the (u-38) diagram are shown by the coolest stars. No very extensive work on classification with these filters for B stars of differing luminosity has been published.

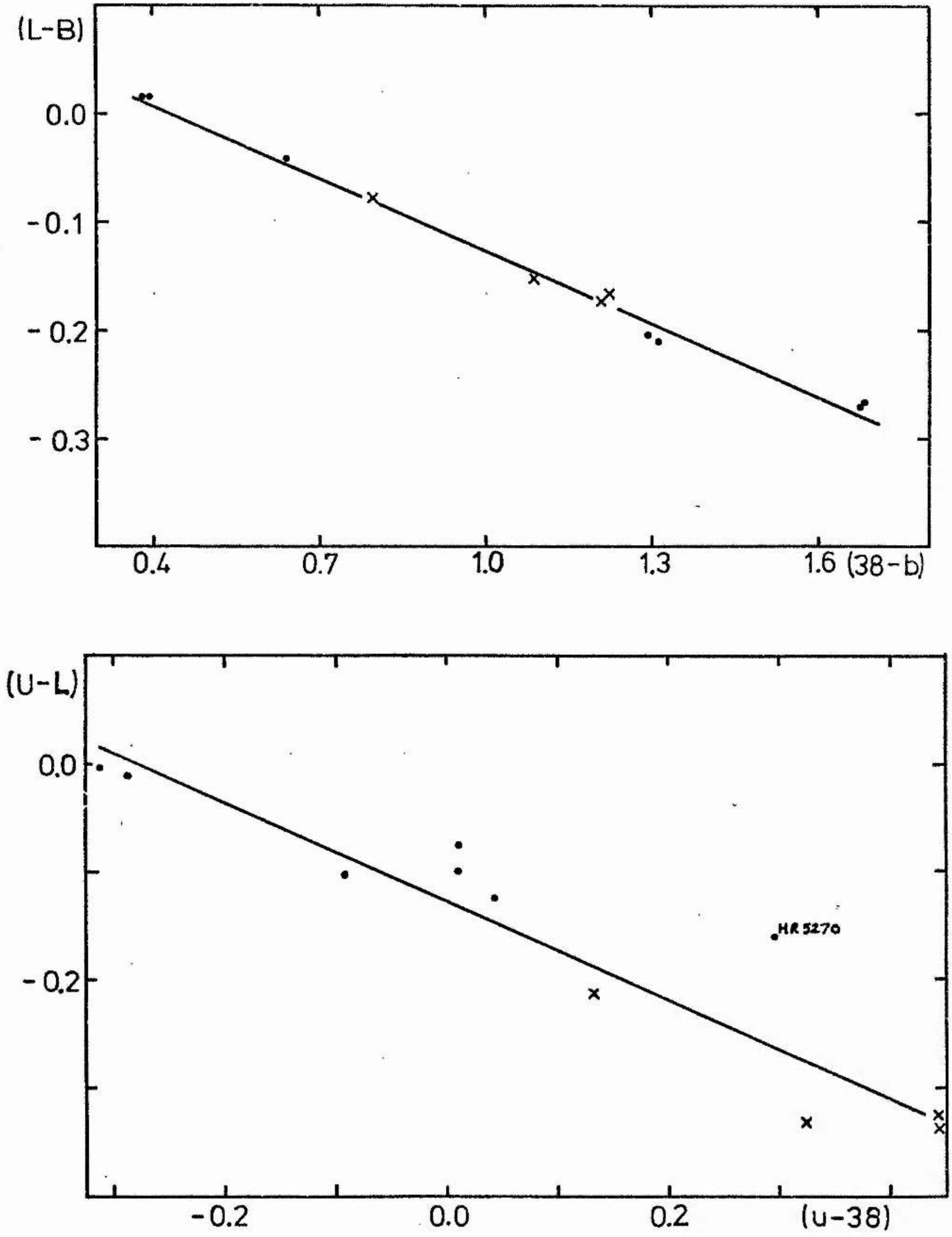


Figure 4.9 Comparison of (u-38) and (38-b) with the Walraven (U-L) and (L-B) Colours. Crosses are stars from Graham (1967) and dots are stars from Walraven and Walraven (1960).

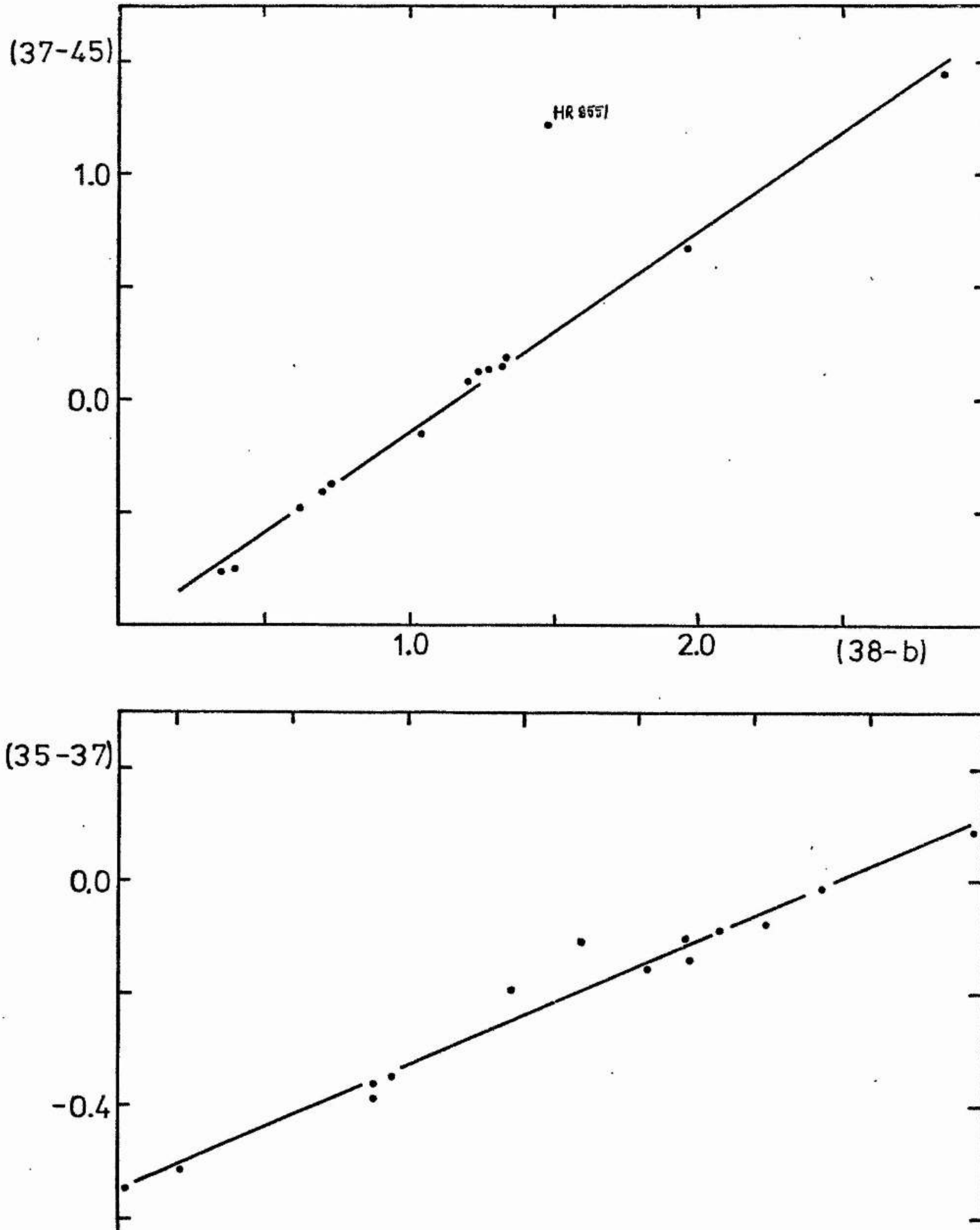


Figure 4.10 Comparison of (u-38) and (38-b) with Johnson's (35-37) and (37-45) Colours

c) The Borgman System

Borgman (1960) used a system of seven filters with filters R, Q, P, N and M centred at 3295, 3560, 3750, 4055 and 4550 A respectively. The corresponding halfwidths were 80, 90, 110, 200 and 200 A. Hence the filters Q, P and M roughly correspond to the u, 38 and b filters.

Among the reddening free parameters used by Borgman and Blaauw (1964) were

$$\beta = (P-N) - 0.701(N-M)$$

$$\gamma = (Q-N) - 1.068(N-M)$$

$$\delta = (R-Q) - 0.882(N-M)$$

The β parameter measures the effect of the high series number Balmer lines and has a range of 0.6 from BOV to AOV compared with the range of 0.7 for [38-b]. The γ parameter measures the height of the Balmer discontinuity and the δ parameter the difference in the continuum gradient either side of the discontinuity. Good separation of B dwarfs, giants and supergiants was found in the (β) - (δ) diagram. β has been calibrated against absolute magnitude by Borgman and Blaauw and provides absolute magnitudes with an error of ± 0.48. This error appears to be caused by intrinsic scatter rather than observational inaccuracy. There are only two stars in common between the Borgman stars and those studied with the 38 filter.

d) The Vilnius System

This system of eight glass filters was intended for spectral classification of all types of star. The system was calibrated using observed stellar energy distributions and the Whitford interstellar extinction curve. Details of the calibration process and the system in general are given by Straizys (1970), Sudzius et al. (1970), Sviderskiene and Straižys (1971) and other Vilnius publications. The filters of interest for comparison with the 38 filter are U, P, X, Y and Z which are centred at 3450, 3740, 4050, 4660 and 5160 A with halfwidths of 400, 260, 220, 260 and 210 A respectively. Reddening-free indices of the form

$$Q_{abc} = (m_a - m_b) - \frac{E_{a-b}}{E_{b-c}}(m_b - m_c)$$

were used. The $Q_{UPY} - Q_{PYZ}$ diagrams show separation of B dwarfs, giants and supergiants similar to that obtained with the Borgman system. There are only four stars common to the 38 photometry and the Vilnius photometry.

e) The DAO System of Slot Filters

Slots, placed in a dispersed beam of star light, act as filters for this system. A photomultiplier is placed behind each filter. The construction of the photometer is discussed by Walker et al. (1970). The slots are centred at 3500, 3775, 4150, 5410 and 5590 A with widths of 100, 150, 500, 720 and 360 A. Hill, Morris and Walker (1971) give the initial results for the DAO system. Two indices of the same form as those in the Vilnius system are used. Q(35) and Q(38) are derived from the 35, 44 and 54 filters and the 38, 44 and 54 filters respectively. Q(38) is well correlated with the Hβ index and for dwarfs this relationship has two linear sections meeting at B5. The gradient of the earlier section varies for different luminosity classes. Good separation is found between luminosity classes in the Q(38) - Q(35) diagram. Very limited overlap exists between the stars observed in the DAO system and with our 38 filter.

Two other systems, which have been confined mainly to red stars, are the DDO system of McClure and Van den Bergh (1968) and the Neff and Travis (1967) system. The former has a 38 filter centred at 3800A with a halfwidth of 172A while the latter has four filters centred at 3300, 3700, 4700 and 5500 A. The Neff and Travis system is somewhat similar to the Strömgren system with the v filter replaced by the filter at 3700A.

4.9 Appraisal of the 38 Filter

The major question which must be considered is what advantage does this particular Balmer jump filter have over the other filters discussed in the previous section. The primary advantage is that the filter is an addition to a widely used photometric system with well defined characteristics rather than being part of a completely new system. When used with the Strömgren system the filter provides a parameter, [38-b], which is linearly related to the Crawford $H\beta$ index and hence may be used to estimate absolute magnitudes for B stars. This result was obtained using an intermediate filter with consequent improvement in the limiting magnitude for the same telescope. This was balanced by the need to keep the filter as narrow as possible to maximise the range of the indices. Hence [38-b] has over twice the range of the β index although at present the errors are also proportionally larger.

It can be seen that the 38 filter has considerable potential and further work could provide a more accurately defined system with increased classification and luminosity determination capabilities. As a test of the derived relationships, photometry of some apparently normal faint blue stars was used to derive absolute magnitudes and distances. This is given in Chapter 7. Let it suffice to say here that in general the results seem reasonable.

CHAPTER 5

HeII 4686 PHOTOMETRY

5.1 Introduction

The difficulties in the classification of O, sdO and DO stars have been discussed in Section 3.6. The effect of surface gravity on the HeII λ4686 line has been used in an attempt to separate sdO and DO stars and to provide a luminosity-dependent parameter for O stars.

The high luminosity of Population I O stars makes them very important in the study of galactic structure and the interstellar medium. Since these stars are very young, hot massive objects and often associated with nebulosity, their properties are also important for the study of stellar formation and evolution. It is thus of interest to find parameters which provide independent estimates for the basic properties of these stars. The sdO stars are important for different reasons, being old highly evolved objects whose properties place constraints on stellar evolution calculations.

a) O Star Classification Systems

The development of a classification scheme for O stars has been a continuous process since Plaskett (1922) defined O stars as those showing the HeII λ4542 absorption line. Plaskett and Pearce (1931) elaborated this by the introduction of the letter f to denote stars with NIII λλ4634-41 in emission and HeII λ4686 in emission. In the MK system (Morgan et al., 1943) the spectral type for O stars is defined by the ratio of HeI $\lambda 4471$ to HeII $\lambda 4542$ and this has been continued in the two main classification systems presently in use. Conti and Alschuler (1971) produced a classification system based on equivalent widths from high dispersion (16A/mm) spectra. The primary luminosity indicator is the strength of the SiIV absorption lines. Conti and Alschuler concluded from a comparison of the HeII $\lambda 4686$ and HeI $\lambda 4542$ line strengths that the HeII line was only a fair luminosity indicator. Walborn (1971,1972) has developed a classification system based on 63A/mm spectra and an empirically defined grid of standard stars. This system is still developing and now provides a sophisticated system of classification including such details as carbon and nitrogen deficiencies (Walborn, 1976). The luminosity criteria are, in addition to the SiIV lines for the cooler stars, mainly based on the emission lines, including HeII $\lambda 4686$, seen in the spectra of the more luminous stars. Walborn (1972) examined the conclusion of Conti and Alschuler concerning the $\lambda 4686$ line and showed several flaws in their argument. His conclusion was that the nature of the line - absorption, filled absorption or emission - was well correlated with absolute magnitude. The correlation between these classification systems and the physical properties of O stars are discussed by Conti (1975).

b) The Landolt Photometric Index, h

Landolt (1970) used a twin filter system based on the HeII $\lambda 4686$ line and derived an index which he called h. His wide and narrow filters had halfwidths of 192A and 42A respectively. The results showed a reasonable separation of Of from O stars and a slight correlation between h and absolute magnitude. Landolt concluded that this method could derive absolute magnitudes with an error of $\pm 0\overset{m}{.}5$. This seems optimistic when his h - M_v diagram is examined carefully and it will be shown later that the situation is more complicated than would appear from Landolt's work. The general consensus is that the main problem with the Landolt system was that the halfwidth of the narrow filter was too great (Conti, 1976).

5.2 4686 Photoelectric Observations

Two interference filters centred at 4686A with halfwidths of 26A and 150A were used and their transmission curves, taken from the monochromator scans made by the manufacturer, are shown in Fig. 5.1. These halfwidths were chosen in the hope that, by reducing the narrow filter to 26A, better resolution between luminosity classes might be achieved than with the Landolt system.

O stars from the compilation of Cruz-Gonzalez et al. (1974), covering a wide range of spectral type and luminosity class, were observed. High priority was given to Walborn (1972) classification standards and stars with equivalent widths by Conti and Alschuler (1971). In particular, stars in the Sco OB1 association were observed since Schild et al. (1969) have provided reasonably accurate absolute magnitudes for members of this association. Subdwarfs from the St. Andrews faint blue star programme and possible subdwarfs from the TD1 satellite survey (Giddings, 1976) were compared with the other O stars.

The observations were obtained on fifteen nights during the period 1976 August - 1977 September using the S.A.A.O. 1m. and 0.5m.

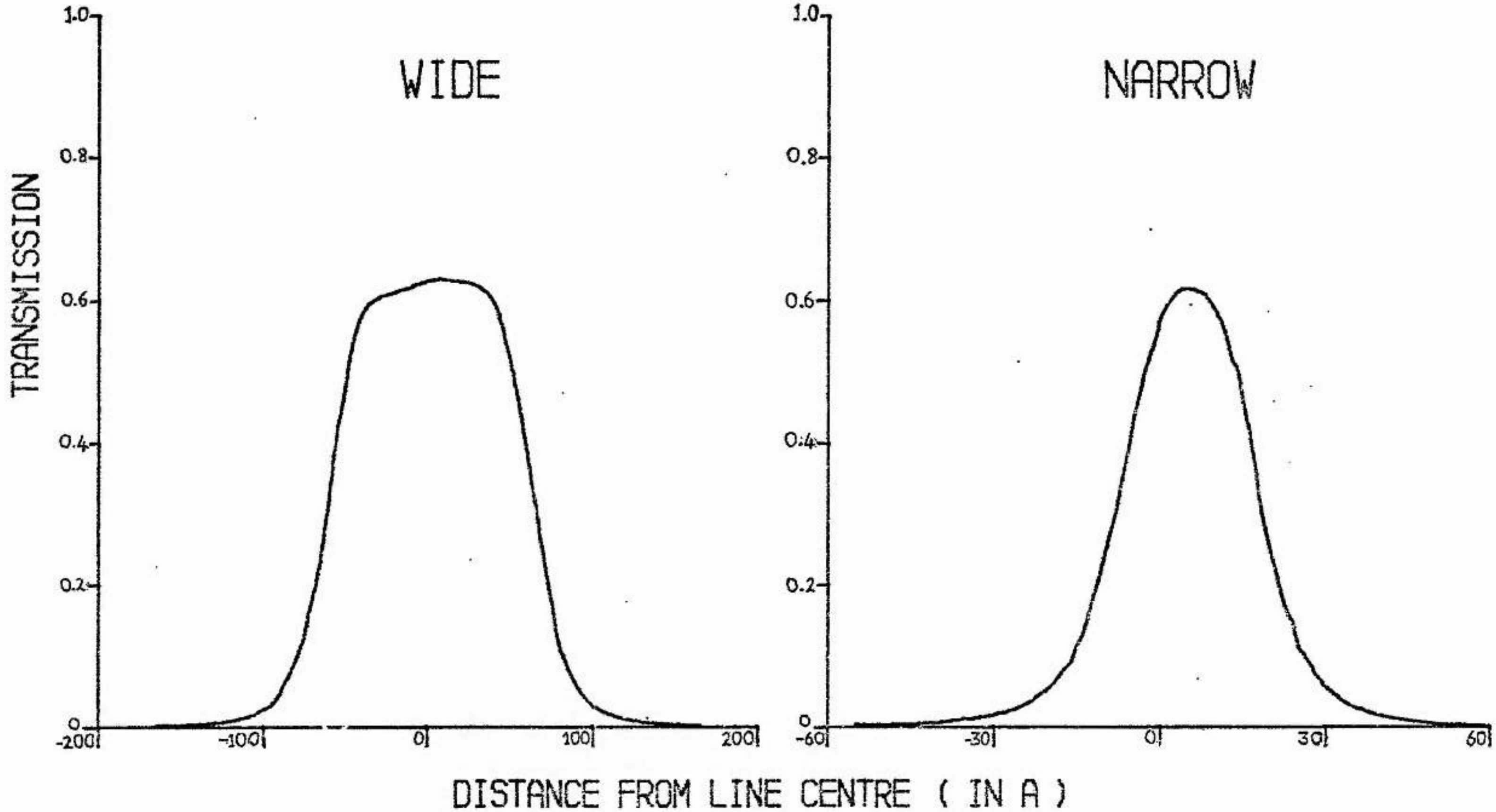


Figure 5.1 Transmission Curves of the 4686 Filters

telescopes. The photometer on the 0.5m. telescope was used in its two-channel mode with the incoming light split by an 80:20 beam-splitter. This allowed simultaneous integration through the wide and narrow filters. Usually six 30 second integrations were made for each star. More were obtained if there was any doubt about the sky conditions or the behaviour of the photometer. Simultaneous observation with both filters is not possible with the 1m. telescope using the St. Andrews photometer and alternate 10 second counts were made through each filter. This procedure is satisfactory if no rapid changes in sky transparency occur. Usually observations for each star were continued until a total count through the narrow filter of 100,000 above sky was obtained. This leads to a quantum noise error of 0.3%, which is equivalent to an error of $0\overset{m}{.}003$ in the 4686 index, and should give indices of the quality necessary to set up a photometric system. Care was taken to exclude, as far as possible, any nearby stars in the crowded Milky Way fields and to obtain sky readings with no stars in or near the aperture. Difficulties were encountered since some stars had close companions or were embedded in bright nebulosity. It is possible that the indices for such stars were altered by these effects.

5.3 Reduction Procedure

Instrumental indices were computed from the counts or signal through each filter after dead time, gain and sky corrections had been made. The indices were defined as

$$2.5 \log(\text{wide signal}/\text{narrow signal}).$$

The results obtained during 1976 August and September with the 1m. telescope were compared and found to agree well. Mean indices were calculated for stars with three or more observations and these were used as initial standard values. Linear least squares fits between the initial standard values and the instrumental indices for each night were calculated and corrections made for any differences in scale factors and zero points between the nights. The instrumental indices of further observations were reduced to this system using a least squares calculation of scale factor and zero point. When additional stars had three consistent observations they were included among the standard stars to extend the system round the sky. Observations from 1977 September 25/26 were used in conjunction with the 1976 August/September results to provide sufficient standard stars for the 1977 January nights. Some of the initial 1976 standard stars were observed rising at the end of the January nights. Their derived indices, using the standards which had been obtained at larger right ascensions, were in good agreement with the original indices. Hence with the 1977 May and September observations, the preliminary standard system has been taken round the sky once with no significant closing errors.

The zero points and scale factors determined for the least squares solutions are listed in Table 5.1. n is the number of standard star observations used in the solution.

The residuals between the observed indices, when reduced to the standard system, and the standard values were examined for systematic effects with time, airmass, V magnitude, hour angle and declination. The program developed to analyse the Strömgren

Table 5.1 Transformation Coefficients to the 4686 Standard System

Date	Telescope	Scale Factor	Zero Point	n
76 Aug 13/14	1m.	0.992 ± 0.035	0.017 ± 0.056	8
76 Aug 18/19	0.5m.	0.340 ± 0.167	1.500 ± 0.058	12
76 Aug 21/22	0.5m.	0.441 ± 0.097	1.492 ± 0.026	20
76 Aug 23/24	0.5m.	0.571 ± 0.116	1.438 ± 0.034	18
76 Sept 2/3	1m.	0.964 ± 0.019	0.058 ± 0.030	11
76 Sept 3/4	1m.	0.989 ± 0.016	0.016 ± 0.026	11
76 Sept 4/5	1m.	1.004 ± 0.029	-0.002 ± 0.046	10
76 Sept 6/7	1m.	1.042 ± 0.004	-0.068 ± 0.006	5
77 Jan 28/29	1m.	0.988 ± 0.018	0.010 ± 0.030	4
77 Jan 29/30	1m.	0.999 ± 0.127	-0.008 ± 0.207	4
77 Jan 30/31	1m.	0.994 ± 0.062	-0.001 ± 0.101	5
77 Feb 1/2	1m.	0.934 ± 0.039	0.098 ± 0.063	6
77 May 9/10	0.5m.	-0.393 ± 0.083	1.747 ± 0.029	13
77 Sept 21/22	1m.	1.006 ± 0.269	-0.027 ± 0.438	5
77 Sept 25/26	1m.	0.946 ± 0.062	0.090 ± 0.099	18

residuals (see Section 3.4) was adapted to handle the 4686 residuals. Linear and quadratic fits were used for the temporal variations, which were the only effects found in the data. The time drifts were particularly strong for the 1976 August 0.5m. observations, when corrections of up to $0\overset{m}{.}015$ had to be applied. For the 1977 September 21/22 observations the variations were complicated and corrections were made from a hand-drawn curve through the residuals. The lack of any correlation with airmass is to be expected since the filters have the same central wavelength.

5.4 Results

The mean indices derived for the galactic plane O stars are listed in Table 5.2 and those for the sdO and B stars in Table 5.3. The tables are arranged as follows:-

Column	
1	The star name.
2	Any alternate name.
3,4	The mean index, I4686, with its standard deviation, σ.
5	The number of observations, n.
6,7	A spectral classification and an indication of its quality. The quality, in decreasing order, is denoted by 1, 2 or 3. These represent classifications by Walborn (1971,1972), Conti and his colleagues (Conti and Alschuler (1971) , Conti and Frost (1977)) and any other source, respectively.
8	A mean equivalent width for HeII λ4686 from Conti and Alschuler (1971), Conti and Frost (1977), Heap (1971),

Baschek and Scholz (1971), Greenstein and Sargent (1974) and Kudritzki and Simon (1978). Emission is considered as negative equivalent width.

9 Any comments. M, C and N denote a binary or multiple system, a bright close companion and bright nebulosity surrounding the star, respectively.

The mean error in a single observation is ±0.0035 from 383 observations of 94 stars, excluding HD 152408 and HD 57060 which are known to show emission line variability (Hutchings (1968,1977)), and HD 155913, HD 150135 and HD 150958 which have standard deviations greater than three times the mean error in a single observation. This is close to that expected if the count above sky was 10^5, which was usually the case. It seems likely that a number of Of stars show changes in the λ4686 emission profile (Conti (1976), Conti and Alschuler (1971)) and some variability in the 4686 index is expected for such stars.

For the six B stars in Table 5.3 the mean index is 1.6079 ±0.0031(s.d.) and this may be taken to represent the index for stars showing no HeII λ4686 line and no NIII emission. In general this means that indices less than 1.608 represent emission in the 4686 line while indices greater than this value are from absorption lines. However as Conti (1975) shows the NIII λλ4634-41 emission line can be formed without the presence of an extended atmosphere which is necessary for the formation of the λ4686 emission. Thus the NIII emission appears at slightly lower luminosities than the λ4686 emission and will tend to increase the index for such stars simulating a λ4686 absorption. This trend will quickly be reversed as λ4686 goes into emission for slightly higher luminosities.

Table 5.2 4686 Photometry for O Stars in the Galactic Plane

	Star	Alternate name	I4686	σ	n	Spectral Type	Quality	Equivalent width (mA)	Comments
	HD 36486	δ Ori	1.6151	0.0001	2	O9.5II	1	295	M
	HD 36619		1.6101	0.0069	2	O7	3		
	HD 36841		1.6174		1	O8	3		
	HD 36861	λ Ori	1.6306	0.0008	2	O8III((f))	1	746	M
*	HD 37022	θ^1 c Ori	1.6135	0.0032	8	O7V		347	C,N
*	HD 37041	θ^2 A Ori	1.6140	0.0060	5	O9V		447	
	HD 37043	ι Ori	1.6285		1	O9III	1	447	M
*	HD 38666	μ Col	1.6199	0.0028	18	O9.5V	1	692	
	HD 41997		1.6224		1	O7.5V(n)	1		
	HD 46150	12 Mon	1.6335	0.0030	4	O5V((f))		800	
	HD 46223		1.6361	0.0060	2	O4V((f))	1	696	
	HD 46966		1.6303	0.0018	3	O8V	1	575	
	HD 47129		1.5970	0.0016	2	O8p	1	0	M

	Star	Alternate name	I4686	σ	n	Spectral Type	Quality	Equivalent width (mA)	Comments
*	HD 47432		1.6051	0.0045	5	09.7Ib	1	275	
	HD 47839	15 Mon	1.6200	0.0014	4	07V((f))	1	631	M
	HD 48099		1.6299	0.0014	3	07V	1	617	
	HD 48279		1.6354	0.0005	2	08V	1	912	M
	HD 53667		1.6115	0.0023	3	05	3	14	
	HD 53975		1.6305	0.0023	3	07.5V	1	832	
	HD 54662		1.6347	0.0025	3	06.5V	1	915	
	HD 55879		1.6145	0.0017	3	09.5II-III	1		
	HD 57060	29 CMa	1.5793	Var?	18	07Ia:fp var	1	813(var)	M
*	HD 57061	τ CMa	1.6014	0.0026	5	09II	1	295	
	HD 57682		1.6224	0.0044	3	09IV	1	603	
	HD 66811	ζ Pup	1.5753		1	04I(n)f	1	2466	
	HD 68450		1.6130	0.0025	4	09.7Ib-II	1		
	HD 69464		1.6139	0.0013	2	06.5Ib(f)	1		
	HD 75211		1.6151	0.0019	3	09Ib	1		

Star	Alternate name	I_{4686}	σ	n	Spectral Type	Quality	Equivalent width (mA)	Comments
HD 75222		1.6052	0.0065	3	O9.7Iab	1		
HD 75759		1.6238	0.0009	4	O9Vn	1		M
HD 76556		1.6172	0.0011	2	O5.5Vn((f))	1		
HD 78344		1.6137	0.0017	2	O9.5Ia	3		
HD 298425		1.6203		1	O9V	3		
HD 298429		1.6277		1	O9III	3		
HD 91824		1.6378	0.0033	2	O7V((f))	1		
HD 93028		1.6246	0.0046	2	O9V	1		
HD 93205		1.6253		1	O3V+O8V	1		M
HD 93250		1.6065		1	O3V((f))	1	537	
HD 101190		1.6273	0.0012	3	O6V((f))	1		M
HD 105056		1.6014	0.0029	5	O9.7IaeN	1		Var
HD 110360		1.6381	0.0055	4	O7.5V	3		
HD 112244		1.5986	0.0030	9	O8.5Iab(f)	1		
HD 115455		1.6182	0.0043	4	O7.5III((f))	1		

	Star	Alternate name	I4686	σ	n	Spectral Type	Quality	Equivalent width (mA)	Comments
	HD 116852		1.6186		1	O9III	3		
	HD 123056		1.6160	0.0049	5	O9.5V((n))	1		
*	HD 124314		1.6189	0.0029	11	O6V(n)((f))	1		M
	HD 124979		1.6207		1	O8.5	3		
	HD 125206		1.6163	0.0045	8	O9.5IV:(n)	1		
	HD 130298		1.6237	0.0064	2	O7.5	3		
	HD 135240	δ Cir	1.6097	0.0034	12	O7.5III((f))	1		M
*	HD 135591		1.6197	0.0035	9	O7.5III((f))	1		
	HD 329905		1.6079	0.0080	3	O9I	3		
*	CPD-53 6950		1.6107	0.0064	7	O9.5II	2		
	HD 144647		1.6155		1	O8V	3		
	HD 144695		1.6175		1	O9V	3		
	HD 144900		1.6130		1	O9III-V	3		
	HD 144918		1.6098		1	O7V	3		
	HD 147331		1.6007	0.0065	2	O9.5Iab	2		
	HD 148546		1.6009	0.0057	7	O9Ia	1		

Star	Alternate name	I4686	σ	n	Spectral Type	Quality	Equivalent width (mA)	Comments
HD 149038	μ Nor	1.5986	0.0034	12	09.7Iab	1		
HD 149404		1.5945	0.0060	5	09Ia	1		
HD 149452		1.6156	0.0065	2	09V	3		
HD 149757	ζ Oph	1.6131	0.0075	4	09V	2		
HD 150135		1.6111	Var?	2	06.5V	3		
HD 150136		1.6126	0.0088	2	05III	3		
HD 150475		1.6098		1	08.5V	3		
HD 150958		1.5816	Var?	3	06.5Ia(n)f+			
HD 328856		1.6028	0.0011	3	09.5III	3		
HD 151003		1.6009		1	09II	1		
HD 151018		1.5997		1	09.5I			
* HD 151804		1.5950	0.0036	9	08Iaf	1	-603	
HD 152003		1.6000		1	09.7Iab	1		
HD 152147		1.6072		1	09.7Ib	1		
HD 152218		1.6040	0.0050	2	09.5IV(n)	1		

	Star	Alternate name	I4686	σ	n	Spectral Type	Quality	Equivalent width (mA)	Comments
*	HD 152233		1.6102	0.0028	9	O6III:(f)p	1	162	
	HD 152246		1.6206		1	O9III-IV((n))	2		
*	HD 152248		1.6014	0.0027	6	O7Ib:(n)fp	1		M
*	HD 152249		1.6074	0.0019	6	O9.5IabC	1	162	
	HD 152405		1.6067		1	O9.7Ib-II	1		
	HD 152408		1.5527	Var	13	O8:Iafpe	1	-3311	
	HD 152424		1.6038	0.0001	2	O9.7IaC	1		M
	HD 152723		1.6272		1	O6.5III(f)	1		M
	HD 153426		1.6118	0.0065	3	O9II-III	1		
	HD 153919		1.5701	0.0006	2	O6.5Iaf+	1		
	HD 154368		1.6012		1	O9.5Iab	1		
*	HD 154643		1.6115	0.0031	5	O9.5V			
	HD 155913		1.6193	Var?	4	O5Vn((f))	1		
	HD 156212		1.6076	0.0030	4	O9.7Iab	1		
	HD 156359		1.6031	0.0013	2	O9III			

	Star	Alternate name	I4686	σ	n	Spectral Type	Quality	Equivalent width (mA)	Comments
	HD 157857		1.6228	0.0029	4	06.5III(f)	1	214	
	HD 158186		1.6221	0.0108	2	09.5V	3		
	HD 159176		1.6241	0.0019	3	07V+07V	1		C
	HD 161853		1.6275	0.0033	2	08V((n))	1		
*	HD 162978	63 Oph	1.6171	0.0037	6	07.5II((f))	1	468	
	HD 163758		1.6019	0.0047	2	06.5Iaf	1		
*	HD 163800		1.6268	0.0035	8	07III((f))	1	575	
*	HD 163892		1.6174	0.0011	6	09IV((n))	1	661	
	HD 164438		1.6119	0.0017	2	09III	2	562	
	HD 164492		1.6363	0.0059	2	07.5III((f))	1	776	C,N
	HD 164794	9 Sgr	1.6249	0.0087	4	04:V((f))	1	913	N
	HD 164816		1.5832		1	09.5III-IV(n)	1		N
*	HD 165052		1.6310	0.0042	6	06.5V(n)((f))	1	832	M,N
	HD 165921		1.6267	0.0067	2	07.5V	3	407	
	HD 166546		1.6184	0.0045	3	09.5II-III	1	513	

	Star	Alternate name	I4686	σ	n	Spectral Type	Quality	Equivalent width (mA)	Comments
	HD 166734		1.6037		1	O7Ib(f)+O8-9I	1	-363	M
	HD 167263	16 Sgr	1.6166	0.0068	3	O9.5II-III((n))	1	437	
	HD 167264	15 Sgr	1.6131		1	O9.7Iab	1		
	HD 167771		1.6198	0.0007	2	O7III:(n)((f))	1	398	M
	HD 167971		1.5958	0.0002	2	O8Ib(f)p	1	324	
	HD 168075		1.6470	0.0059	2	O6.5IIIf	2	832	
	HD 168112		1.6281	0.0065	2	O5III(f)	1	380	
	HD 168504		1.6365	0.0059	2	O8III	2		
	HD 169582		1.6150		1	O6If	1	0	
	HD 171589		1.6187	0.0045	5	O7III(f)	1	347	
	HD 173010		1.5919	0.0070	2	O9.5Ia	3		
	HD 175514		1.6356	0.0105	3	O8V	3		M
*	HD 175754		1.6137	0.0039	7	O8II((f))	1	355	
*	HD 175876		1.6233	0.0020	7	O6.5III(n)(f)	1	339	M
	HD 188001	9 Sge	1.6045	0.0048	2	O7.5Iaf	2	-182	M

Table 5.3 4686 Photometry for sdO and B Stars

Star	Alternate name	I4686	σ	n	Spectral type	Source	Comments
PHL 829		1.6155		1	sdO	(6)	Planetary Nebula
PHL 6783	FB 10	1.6235		1	sdO+	(4)	M
PHL 1556		1.6604	0.0005	3	sdO	(5)	Planetary Nebula
HD 36512	ν Ori	1.6133	0.0021	4	BOV	(2)	
HD 36960A		1.6080	0.0014	3	B0.5V	(2)	
HD 36960B		1.6073	0.0038	3	B1V	(2)	
* HD 49798		1.6654	0.0011	8	sdO	(3)	M
CD-31°4800		1.6764	0.0028	2	sdO,DO	(1)	
Abell 36	FB 138	1.6578		1	sdO	(1),(4)	
HD 127493	FB 150	1.6693		1	sdO	(1),(4)	
HD 171858		1.6080		1	sdB	(1)	
F 110	FB 186	1.6325		1	sdO	(4),(5)	
HD 215573	ξ Oct , HR 8663	1.6068	0.0025	2	B5V	(2)	
HD 223145	σ Phe , HR 9006	1.6038	0.0059	6	B3V	(2)	

5.5 Comparison of the 4686 Index with Physical Properties

The relationship between the index and the equivalent width of the HeII λ4686 line is shown in Fig. 5.2. Most stars are represented by filled circles. Open circles denote those stars showing variability, open squares subdwarfs and crosses are used where only an upper limit is given for the equivalent width. The errors in the equivalent widths at about 20% are large compared with the photometric errors. There is a tendency for giants to have smaller equivalent widths than dwarfs with the same 4686 index but no complete separation is found. This behaviour is probably due to the presence of NIII emission in the giants but not in the dwarfs. From Fig. 5.2 it is reasonable to conclude that the 4686 index provides a measure of the equivalent width of the HeII λ4686 line.

The mean indices for stars of different spectral types are given in Table 5.4 using the Walborn classifications. It is important to use a homogeneous set of classifications when dealing with O stars since there are often systematic differences between the results of different workers. For instance classifications by Conti are often one spectral type cooler than those of Walborn for the middle O stars. From Table 5.4 it is clear that the λ4686 line classification criteria for luminosity class estimation is reflected in the 4686 indices with a general decrease of the index with luminosity for each spectral type. However there is overlap between luminosity classes and only the luminosity class I stars are uniquely separated. Giants and dwarfs are only marginally differentiated and in fact at O5 the mean giant index is greater than that for

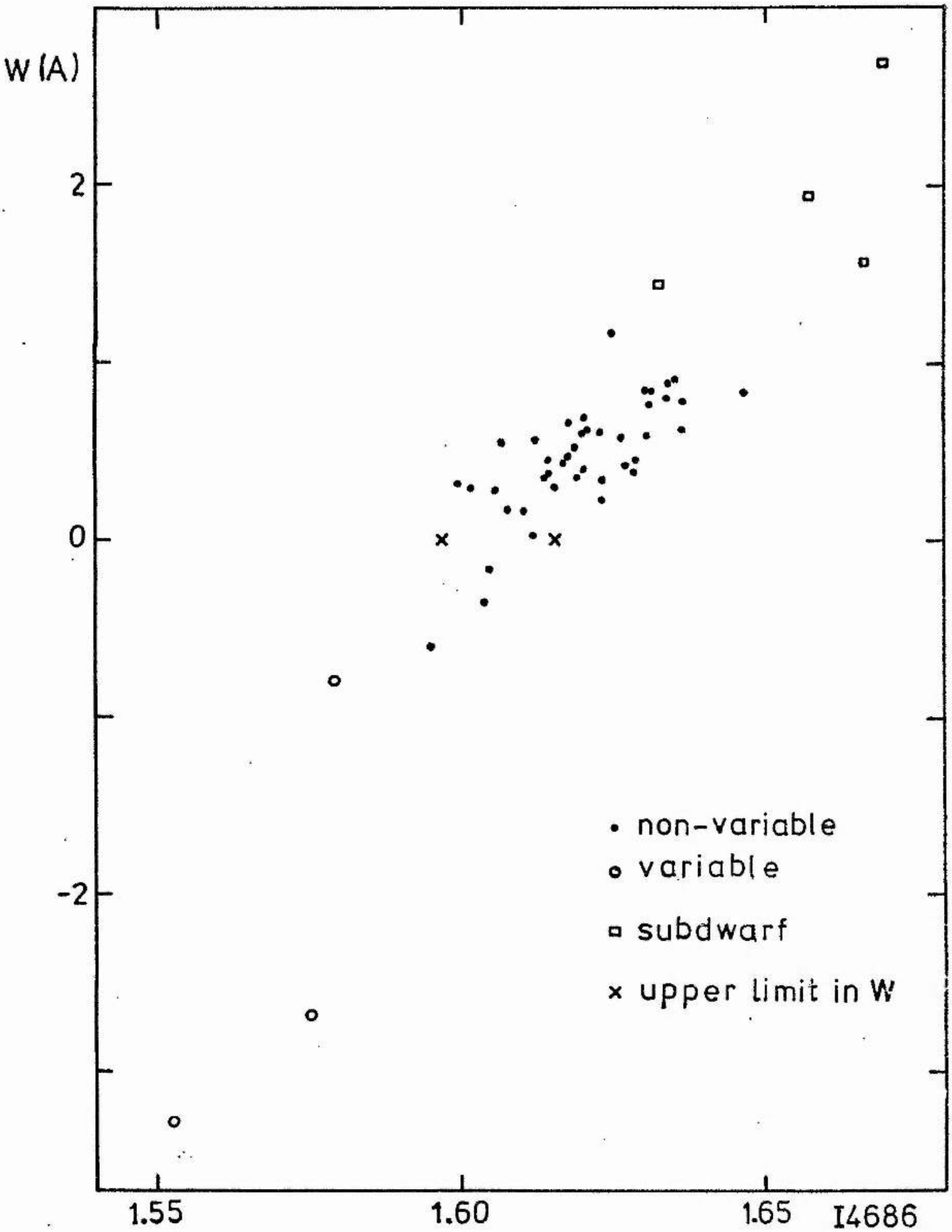


Figure 5.2 Mean HeII λ4686 Equivalent Widths against the 4686 Index.

Table 5.4 Mean 4686 Indices for Walborn Spectral Classifications

	I	II	III(+II-III)	IV(+III-IV)	V
B0					1.6099
O9.7	1.6038				
O9.5	1.6057	1.6151	1.6175	1.6110	1.6191
O9	1.6009	1.6013	1.6160	1.6191	1.6241
O8.5	1.5986				
O8	1.5739	1.6137	1.6306		1.6310
O7.5		1.6171	1.6149		1.6285
O7	1.5856	1.6187	1.6255		1.6265
O6.5	1.5953		1.6235		1.6322
O6	1.6150		1.6102		1.6207
O5.5					1.6172
O5			1.6281		1.6193
O4	1.5753				1.6286
O3					1.6159

dwarfs. The sdO stars fall into two groups. Five stars have a mean index of 1.6659 ± 0.0074(s.d.) while PHL 829, PHL 6783 and F 110 have lower values. These three stars have only one observation each and are among the faintest objects observed. PHL 6783 has a red companion (Greenstein and Sargent, 1974) while PHL 829 is the nucleus of a planetary nebula. No obvious peculiarity is known for F 110.

The relationship between the 4686 index and absolute magnitude is of importance but is complicated by factors other than the strength of the λ4686 line. The 4686 index - M_V diagrams, using absolute magnitudes from Hutchings (1976), Walborn (1971,1972) and Conti (Conti and Alschuler (1971), Conti and Burnichon (1975)) are shown in Figs. 5.3 a-c and that involving the absolute bolometric magnitudes derived by Conti and Burnichon (1975) in Fig. 5.3 d. The symbols are filled circles for dwarfs, open diamonds for subgiants, open circles for giants, horizontal crosses for luminosity class II and diagonal crosses for luminosity class I. The increasing size of the symbols indicates 1, 2-3 and > 3 observations. The error bar for M_V in Figs. 5.3 b and c is probably a conservative error of the real error. The values derived by Walborn and Conti for M_V are not strictly independent since they used the same sources for many associations although the criteria imposed were different.

Clearly, despite the variation in detail between Figs. 5.3 a-c, there are common trends. The index for dwarfs increases to a maximum at about O5 or O6 and then decreases. This is the cause of the "tail" of points diverging from a possible straight line fit. The supergiant which is well removed from other points is HD 152408.

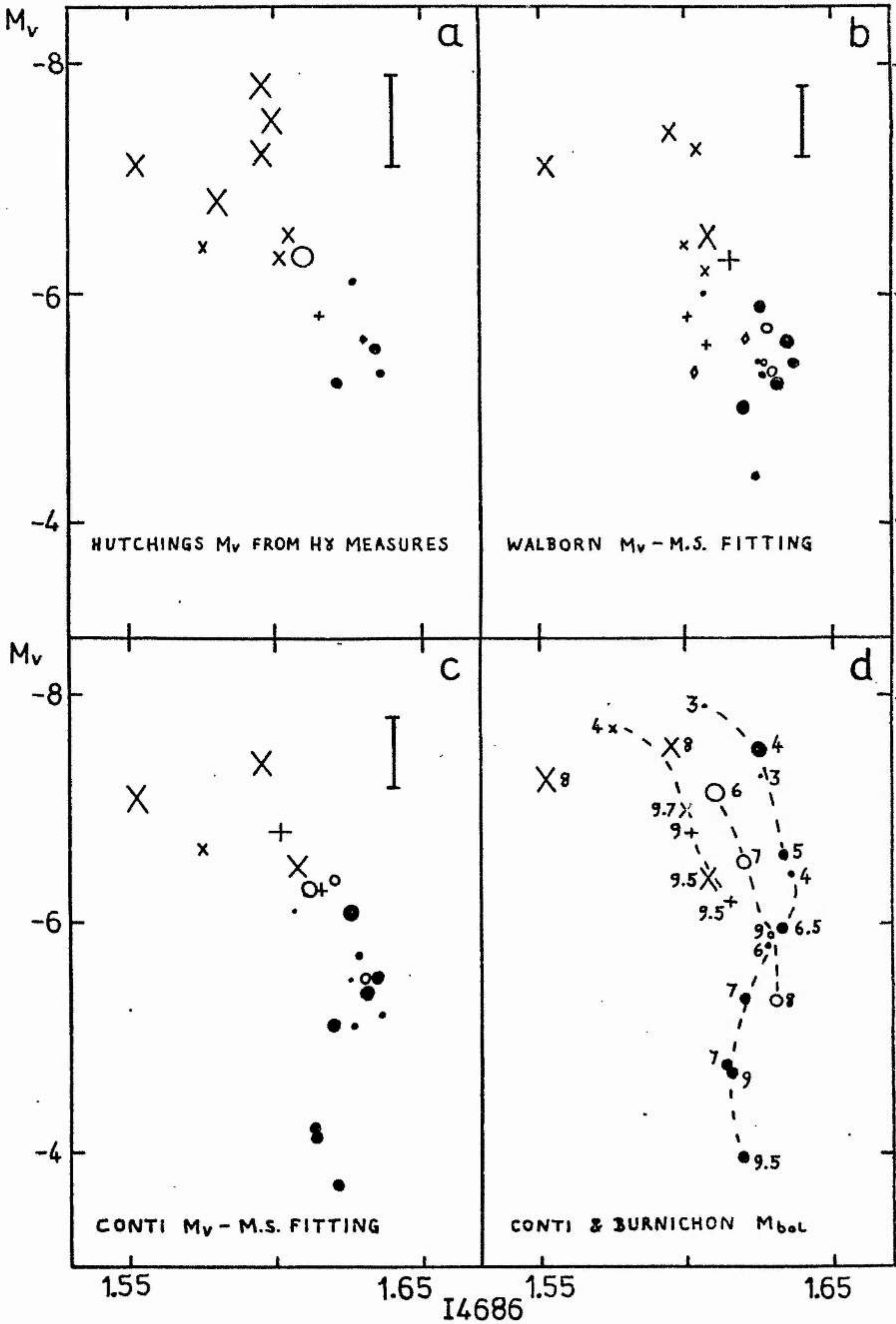


Figure 5.3 a-d The Relationship between Absolute Magnitude and the 4686 Index

Probably Fig. 5.3d is the most revealing showing that the giant index behaves monotonically while the dwarf index peaks.

Although it is quite possible to fit a straight line to the I4686 - M_V diagrams, the evidence is that this is a far too simplistic approach. For instance Fig. 5.3 b gives a linear fit with a mean error of 0.52. This is very much in agreement with Landolt's result but is only possible because fewer luminous stars are present. We must conclude that there is no simple one-to-one relationship between the 4686 index and absolute magnitude but that the determination of absolute visual and bolometric magnitude, when a spectral classification is available, appears possible.

The behaviour of the 4686 index with surface gravity, g, was investigated using the relationship

$$g = 2.738 \times 10^4 \frac{M\,T^4}{L_{bol}}$$

where M, T and L_{bol} are the mass, effective temperature and total luminosity of the star in solar units. This equation is derived directly from the definition of surface gravity, $g = g_{\odot}M/R^2$, and the Stefan-Boltzman Law. The constant 2.738×10^4 is the solar surface gravity (Gray, 1976).

From Fig. 1 of Conti and Burnichon (1975) it is possible to determine an approximate mass for each star. This procedure is probably valid for dwarfs and possibly valid for giants but must lead to erroneous results for supergiants which will have lost mass in their evolution and have high mass loss rates at present. When plotted as an I4686 - log g diagram the results are disappointing since the giants and dwarfs have much the same indices but differing gravities. This produces a large scatter. However the underlying trend is of decreasing index with decreasing gravity.

5.6 Comparison with Model Atmosphere Predictions

Since no known DO stars were observed due to their faintness and one of the aims of the 4686 index was the separation of DO and sdO stars, the behaviour of theoretical 4686 indices has been studied. The non-LTE models of Kudritzki (1976) were used to calculate the theoretical indices. Kudritzki (1977,1978) provided line depths, $P(\Delta\lambda)$, at $\Delta\lambda(A)$ = 0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0 and 5.0. From the last two points an extrapolation of the form

$$1 - P(\Delta\lambda) = c / \Delta\lambda^{\alpha},$$

where c and α are constants, was calculated to represent the wings of the line. The derived line profile was combined with the filter transmission curves and the resultant signals were integrated numerically using Simpson's rule. The theoretical index was derived as 2.5 log(wide signal/narrow signal).

A detailed calculation was made for the subdwarf HD 49798 for which Kudritzki and Simon (1978) have performed a fine abundance analysis. The effect of the HeII λ4542 and HeI λ4713 lines was included as was the shape of the continuous flux distribution. The resultant theoretical index was 1.6700 compared with an observed value of 1.6654. If the effect of the λ4542 and λ4713 lines is removed, the theoretical index becomes 1.6688. This shows that neglecting these lines has an effect less than the error in a single 4686 observation. A further check was made using two coude spectra of ζ Pup (HD 6681) obtained by Dr. G. Wegner during the same week as the single 4686 observation for this star. Dr. Wegner kindly supplied rectified intensity tracings of the 4500 - 4900 A spectral region for both plates. The spectra show strong emission at HeII λ4686 and NIII $\lambda\lambda$4634, 4640-2 with absorption lines at HeII λ4542 and Hβ. The tracings were digitised manually and average intensities calculated for the wavelengths at which the filter transmission values were known. These intensities were combined with the filter transmission curves and a theoretical index was derived, as before. The agreement was less satisfactory with theoretical and observed indices of 1.5980 and 1.5753. This difference is six times the error in a single observation and the most likely cause is that the continuum was fitted slightly too high due to the emission lines.

Indices were calculated from the Kudritzki (1976) models in a similar manner to the HD 49798 index. The effects of the λ4542 and λ4713 lines were neglected. The continuous flux of the HD 49798 model was assumed for all the models. This assumption should be valid since the area considered is so far from the peak of the energy distribution that there should be little difference between the models. The derived indices are shown in Table 5.5. Also given are the effective temperature, surface gravity and helium/hydrogen ratio used to calculate the models and the equivalent width derived by Kudritzki. The He/H ratios of 1.0 and 0.1 are appropriate for sdO and Population I O stars respectively. (Kudritzki, 1976). Auer and Mihalas (1972) have also computed models for certain of the parameter combinations with He/H = 0.1 and the computed equivalent widths are

Table 5.5 Theoretical 4686 Indices from the Kudritzki (1976) Models

Teff(10^3 K)	log g	He/H	Equivalent Width (A)	Index
50	5.0	1.0	2.08	1.6763
50	4.5	1.0	1.86	1.6723
50	4.0	1.0	1.60	1.6657
45	5.0	1.0	2.08	1.6760
45	4.5	1.0	1.88	1.6718
45	4.0	1.0	1.60	1.6647
40	5.5	1.0	1.94	1.6727
40	4.5	1.0	1.77	1.6680
40	4.0	1.0	1.57	1.6632
50	5.5	0.1	1.73	1.6688
50	5.0	0.1	1.54	1.6637
50	4.5	0.1	1.35	1.6573
50	4.0	0.1	1.17	1.6527
45	5.5	0.1	1.61	1.6652
45	5.0	0.1	1.47	1.6612
45	4.5	0.1	1.30	1.6562
45	4.0	0.1	1.11	1.6505
40	6.0	0.1	1.23	1.6548
40	5.5	0.1	1.25	1.6548
40	4.5	0.1	1.12	1.6504
40	4.0	0.1	0.99	1.6464

compared with the Kudritzki values in Table 5.6. F denotes models where the Pickering and Balmer lines are coupled and L when this is not the case. A log g of 4.0 has been shown by Auer and Mihalas (1972) to be appropriate for O dwarfs and Conti (1973) has shown that the temperatures 50,000, 45,000 and 40,000 K correspond to spectral types of O4V, O5.5V and O6.5V

Table 5.6 Theoretical Equivalent Widths for HeII λ4686

Teff(10 K)	log g	Kudritzki	Auer and Mihalas (F)	Auer and Mihalas (L)
50	4.5	1.35	1.23	1.22
50	4.0	1.17	0.76	1.16
45	4.5	1.30	1.23	1.49
45	4.0	1.11	0.82	1.19
40	4.5	1.12	1.09	1.32
40	4.0	0.99	0.83	1.14

The theoretical indices from the Kudritzki models for He/H = 0.1 seem too large and this is due to the theoretical equivalent widths being larger than the observed values. In Table 5.2 indices are given for two O4V stars and two O6.5V stars with measured equivalent widths. The mean values are 0.805 and 0.861 for O4V and O6.5V respectively. These are clearly smaller than the theoretical values. Better agreement is found with the Auer and Mihalas F models which should be equivalent to the Kudritzki models. The values from the Kudritzki models for He/H = 1.0 are assumed to be more accurate considering the agreement for HD 49798.

Kudritzki (1978) has not calculated HeII λ4686 line profiles for log g values greater than those shown in Fig. 5.5 but from the trend of the results it is reasonable to expect that stars with log g > 7, i.e. DO stars, would have indices greater than 1.68. None of the subdwarfs so far studied have 4686 indices as large as this. Auer and Mihalas (1972) give models for supergiants but these have no relevance to the observed indices since the effects of extended atmospheres are neglected. This omission keeps the λ4686 line in absorption whereas the observed line is in emission.

CHAPTER 6

IMAGE TUBE SPECTROSCOPY

6.1 Introduction

Spectra have a larger information content than photoelectric photometry since the behaviour of the spectrum is seen over a range of wavelength and differences in line strengths and profiles may be discerned. Counteracting this is the need to use larger telescopes than for instance required to obtain Strömgren photometry.

An extensive programme of spectroscopy was planned to support the photometric survey outlined by Kilkenny and Hill (1975). The ultimate aim is to obtain spectra for most of the southern stars on the photometry programme. Only part of this spectroscopic survey has been carried out as research for this thesis. In fact progress has been slow mainly due to the loss of over two weeks S.A.A.O. 1.9m. observing time due to equipment failure.

The spectra have been used for

i) classification, as a check on the photometric classifications and to study peculiar objects;

ii) radial velocity determination, since a knowledge of the kinematics and velocity variability is of value in the study of faint blue stars;

and iii) line width measurements, which are used to determine surface gravity using the method of Greenstein and Sargent.

6.2 The Spectra

Spectra have been obtained using two similar R.G.O.-designed Cassegrain image tube spectrographs with the S.A.A.O. 1.9m. telescope at Sutherland and the 2.5m. Isaac Newton Telescope (I.N.T.) at the Royal Greenwich Observatory (R.G.O.). The S.A.A.O. telescope was used for three observing sessions during 1976 September, 1976 November and 1977 September. Of the eighteen nights allocated during 1976 November only three were used for spectroscopy due to equipment failure. The I.N.T. was used for one observing session during 1977 March.

The image tubes were EMI 9914 3-stage image intensifiers with S20 photocathodes and P11 phosphors. This type of phosphor gives an image with a peak wavelength of 4600A (EMI standard specification). Both spectrographs were used with f/1.4 solid Maksutov-Cassegrain cameras. Details of the spectrograph construction and general operation may be found in the S.A.A.O. 1977 Facilities Handbook and the Isaac Newton Telescope Facilities Handbook. Baked IIaO plates were used during 1976 September and November. Baked IIIaJ plates were used for the other spectra.

It was attempted to obtain the spectra in as similar manner as possible with both telescopes to allow comparison between spectra obtained on different telescopes. Two dispersions were used, 75A/mm using a 400 groove/mm grating in the 2nd order and 30A/mm using an 830 groove/mm grating also in the 2nd order. The 75A/mm spectra were intended for classification while the 30A/mm spectra were intended for the measurement of line widths.

The stellar spectra were widened electronically using the scanning coils of the image tube to a width of 0.4mm to 0.8mm depending on the magnitude of the star. During 1976 September with the S.A.A.O. 1.9m. spectrograph the arc spectrum was applied with a displacement provided by the image tube magnetic fields. However this resulted in the arc falling on the same portion of the first phosphor as the stellar light and caused arc lines to appear on the stellar spectrum due to persistence effects. Thereafter the arc spectrum was applied using the long slit method in which the light from the arc lamp illuminated the length of the spectrograph slit and the central portion of the slit was masked to protect the stellar spectrum. The plates were processed in the normal fashion using D19 developer and Amfix fixer. Bubble development was used at the I.N.T. and for the 1977 S.A.A.O. spectra.

6.3 Spectral Classification

The spectra have been classified as a check on the classifications derived from Strömgren photometry. The stars which are not subluminous or show major peculiarities have been classified on the MK system (Morgan et al., 1943; Johnson and Morgan, 1953; Morgan and Keenan, 1973). The MK standards for which spectra have been obtained are

HD 42087	B2.5I	HD 116842	A5V
HD 24760	B0.5V	HD 113139	F2V
HD 32630	B3V	HD 204867	G0I
HD 103287	A0V	HD 62509	K0III

These have been supplemented with the atlas of grating spectra by Abt et al. (1968). The subluminous stars were classified by comparison with stars observed by Greenstein and Sargent (1974) and the three southern subdwarfs HD 205805 (sdB), HD 149382 (sdB) and HD 49798 (sdO).

The classifications were made using a Hilger and Watts Spectrocomparator which allows detailed comparison of line strengths by displaying the magnified spectra on a viewing screen. In the case of the 75A/mm spectra the number of the last visible Balmer line, which is the quantum number of the upper level of the line, was estimated since this is a measure of the stellar surface gravity. The classifications are given in Table 6.1, which includes those stars which were suspected to be subluminous, not previously classified or classified by Greenstein and Sargent (1974) as 'normal'. The columns of the table contain

i) the star name and alternate name;

ii) the spectroscopic classification;

iii) the number of the last visible Balmer line, n_m;

iv) the photometric classification and its source;

v) any other spectroscopic classification and its source;

and vi) any comments.

The sources of the classifications are:-

1 Chapter 3 of this thesis

2 Kilkenny, Hill and Brown (1977)

3 Kilkenny (1977)

4 Kilkenny and Hill (1975)

5 Graham (1970)

6 Hill (1970)

7 Greenstein (1960)

8 Feast et al. (1960)

9 Slettebak and Stock (1959)

10 Slettebak, Bahner and Stock (1961)

11 Slettebak, Wright and Graham (1968)

12 Graham and Slettebak (1973)

For the stars HD 205805, HD 149382 and HD 49798 the quantum numbers of the last visible Balmer line are 13, 11 and 10 respectively.

From Table 6.1 it can be seen that there is reasonable agreement between the derived spectral types and both the photometric and the previously published spectroscopic classifications. The typical error appears to be of the order of one spectral subtype. Among the bright stars suspected of subluminosity from Strömgren photometry, only HD 188112 is in fact subluminous. LB 1735 is notable in that it is a normal main sequence B star but has an apparent magnitude of 13.5 and must hence be very distant. This and similar stars are discussed in Section 7.3.

Among the peculiar objects examined were JL 76 and CD-31° 622 which have been classified as DC? by Kilkenny et al. (1977) and Eggen (1976) respectively. Brown and Hill (1977) showed JL 76 to be a B1.5V star with a red companion, which is an M giant if the system is a physical binary, and CD-31° 622 to be a highly metal deficient sdG-K star.

Table 6.1 Spectroscopic Classifications of Faint Blue Stars

Star	Alternate name	Classification	n	Photometric classification	Source	Other spectroscopic classification	Source	Comments
HD 264111	FB 46	B2V	> 11	B1	3			
BD-3° 2179		sdO						
BD+6° 2461	FB 76	B2V	14	sdB?	3			
BD+36° 2242	FB 85	B8:V	> 13	B8	3	A2	9	
HZ 25	FB 97	B2V	16	B2	3	B3Vn	7	
F 64		B4:V	> 12	sdB?	3			
HD 110166	FB 104	B7V	15	B8	3	B7V;B8V	10;11	
HD 146813	FB 164	B1V		B2	3			
BD+13° 3224	FB 168	BIIIp		sdB	3			Helium rich
BD-15° 115	FB 7	B3V	14	B2?sdB?	4	B2V	12	
SB 290		sdB						
TS 192		sdB	> 10	sdB				

Star	Alternate name	Classification	n	Photometric classification	Source	Other spectroscopic classification	Source	Comments
HD 8323	FB 16	B5V		B6	2			
HD 15910		B8-9V	14	Late B				
F 30		B5V	14	B5;B6	4;5			
HD 21305	PHL 1532	B4V		sdB?	2	B5V	6	
PHL 1548		sdB	10					
HD 21996	PHL 4451	B2.5V		B3	2	B5V	6	
LB 1735		B4V	14	B3	4			
LB 3384	HD 270754	B1I	> 12	09(sdB?)	1	B1.5Ia	8	
LB 3422	HD 269050	B1I		sdB?	4	B0Ia	8	
LB 3459	HD 269696	sdO	10	sdO	4			
HD 150055		A0V	12	B9.5	1			
HD 165872	CD-23° 14002	B2V	12	sdB?	2			
HD 171858		sdB		sdB	1			

Star	Alternate name	Classification	n	Photometric classification	Source	Other spectroscopic classification	Source	Comments
HD 188112		sdB		B1.5(sdB?)	1			
JL 82		sdB		sdB	2			
PHL 178		sdO		sdO	1			
HD 213781	FB 180	B7V	15	B6	2			Silicon-star
HD 213728	PHL 1971	B7V	16	B6	2			
CD-35° 15910		sdB		sdB	1			

6.4 Radial Velocities

a) Measurement of the Spectra

Radial velocities have been determined for the 30A/mm spectra obtained using the S.A.A.O. 1.9m. telescope during 1977 September and the I.N.T. in 1976. Spectra obtained at S.A.A.O. before 1977 did not have an arc spectrum suitable for radial velocity determination. S.A.A.O. staff rectified this by the inclusion of a $CuSO_4$ filter in the beam of the Cu/Ar arc, which removed the strong first order lines.

The spectra were measured at R.G.O. using the oscilloscope line scanning measuring machine. The operation of this machine is relatively simple although the initial adjustments are complicated. The spectrum is illuminated by an unfocused beam of light which passes through the spectrum and is then divided by a dichroic filter. This filter transmits the yellow light on to a viewing screen and reflects the blue light on to a rotating quartz block. The blue light is reflected from the quartz block through a dekker, which selects either the star or arc spectrum for measurement, to a IP28 photomultiplier. The signal is amplified and displayed on a cathode ray tube. The cathode ray tube was operated in its double scan mode in which two similar traces are seen but appearing from opposite directions as the spectrum is moved. When the traces for a line coincide, the position of the screw, which is encoded, is printed by pressing a button.

Each line was measured at least four times and usually more in the case of broad stellar lines. The spectrum was measured both in the forward and reverse directions. The plate was rotated between the forward and reverse measurements so that a feature was always approached from the same direction. This procedure helps remove the effect of backlash and any systematic measuring techniques.

b) Choice of Rest Wavelengths

AI and AII arc wavelengths were initially taken from the M.I.T. Wavelength Tables (Harrison, 1969) but it was found that the wavelengths by Moore (1945) gave smaller residuals and these values were adopted. The arc wavelengths used are given in Table 6.2. All the rest wavelengths for the stellar lines were taken from Moore (1945). The lines used for the blue stars are listed by element in Table 6.3 while those for the red radial velocity standards are given in Table 6.4.

c) Reduction Procedure

The measurements were reduced using a FORTRAN program which fitted a polynomial to the wavelengths and positions of the arc lines. The position of the line was calculated as the difference between the forward and reverse measurements. The subroutine used for the least squares calculations was that employed by Hill (1971). This subroutine gives the polynomial of degree less than or equal to p, where in this case p=5, which has the smallest standard deviation. The smallest degree chosen was 3 although most of the polynomials were of degree 4 or 5. The residuals of the fitted arc wavelengths were always less than 0.1A and the mean residual over all the spectra was 0.026A.

The derived polynomial was used to calculate the observed wavelengths of the stellar lines. In the case of lines which were

Table 6.2 Wavelengths of Cu/A Arc Lines

λ	Weight	Element	Comment	λ	Weight	Element	Comment
3946.10	1	AII		4379.74	1	AII	
3948.978	1	AI	AII in MIT Tables	4426.01	1	AII	
4072.20	½	AII	Blend	4474.77	1	AII	
4103.91	1	AII		4481.83	1	AII	
4131.73	1	AII		4510.733	1	AII	
4158.591	1	AI		4545.08	½	AII	Possibly blended
4200.675	½	AII	Possibly blended	4579.39	1	AII	
4259.362	1	AI		4589.93	½	AII	Possibly blended
4272.169	1	AI		4609.60	1	AII	
4277.55	1	AII		4657.94	1	AII	
4300.101	1	AI		4726.91	½	AII	Possibly blended
4333.561	½	AI	Possibly blended	4764.89	1	AII	
4348.11	1	AII		4806.07	1	AII	

Table 6.3 Rest Wavelengths for Lines measured in Spectra of Faint Blue Stars

Element	λ	Comment	Element	λ	Comment
HI	3970.074	Hε	CIII	4070.30	
	4101.737	Hδ		4152.43	
	4340.468	Hγ		4187.05	
				4247.56	
HeI	4009.27			4325.70	
	4026.189			4361.85	
	4120.812			4647.40	
	4143.759			4651.35	
	4168.971			4673.91	
	4387.928				
	4471.477		CIV	4441.81	
HeII	3968.43		NII	4082.28	
	4100.04			4171.608	
	4199.83			4181.17	
	4388.67			4227.749	
	4541.59			4241.80	
	4685.682			4441.99	
				4447.083	
CII	4267.16				
	4744.90				

Element	λ	Comment	Element	λ	Comment
NIII	4097.31		SiIV	4088.862	
	4103.37			4116.103	
	4195.70				
	4215.69		SII	4162.70	
	4284.51			4456.43	
	4323.93			4483.424	
	4353.66			4524.946	
	4523.60				
	4634.16		SIII	4253.593	
				4478.480	
NeII	4224.57				
			FeIII	4139.68	
MgII	4481.327			4211.51	
				4395.78	
SiII	4128.051				
			HgI	4358.34	Night Sky Emission Line
SiIII	4552.65				
	4567.87				
	4574.78				

Table 6.4 Rest Wavelengths for Radial Velocity Standard Lines

Element	λ	Element	λ
MgI	4167.266	FeI	4084.498
			4118.549
CaI	4226.728		4132.06
	4355.096		4150.26
			4172.749
TiI	4535.574		4187.044
			4198.31
TiII	4312.86		4215.43
	4337.916		4247.432
	4395.031		4260.479
	4443.80		4271.764
	4501.27		4280.53
			4307.906
CrI	4274.803		4325.765
	4289.721		4374.495
	4368.252		4383.547
	4399.823		4404.752
	4430.486		4415.125
			4435.151
CrII	4077.50		4447.722
			4459.121
FeI	4005.246		4461.654
	4045.815		4469.381
	4063.597		
	4071.74	SrII	4077.714

measured but not immediately identified, the observed wavelength was calculated and an identification made from this. The radial velocity, V, for each line was then calculated from

$$V = \frac{\Delta\lambda}{\lambda} c$$

where c is the velocity of light and $\Delta\lambda$ is the difference between the observed wavelength and the rest wavelength, λ . This is the well known Doppler effect (Doppler, 1842). Heliocentric corrections were calculated using a program kindly supplied by Dr. P.W. Hill.

d) The Radial Velocities

Mean heliocentric radial velocities were calculated for each spectrum from the individual line velocities. The mean velocities are given in Tables 6.5, 6.6 and 6.7 for the radial velocity standards, stars observed with the I.N.T. and stars observed at S.A.A.O. respectively. The tables contain the name, spectral type, UT date of observation, the mean radial velocity with its standard error and the number of lines measured, n. When two or more velocities have been determined for the same star, the mean velocity is given with its standard error after the individual measures. In Table 6.5 the standard radial velocity from Pearce (1955) is given. In Tables 6.6 and 6.7 the FB number and radial velocity from Greenstein and Sargent (1974) are given if the star was observed by them. Also any other radial velocity determinations are noted.

Table 6.5 Radial Velocities for Standard Stars

Star	Type	Date	R.V.	s.e.	n	Standard velocity	Telescope
β Gem	KOIII	77 III 6.872	+4.3	3.4	12	+3.3	I.N.T.
HD 145001	G8III	77 III 7.225	-6.9	4.7	10	-9.5	I.N.T.
HD 693	F6V	77 IX 18.988	+13.8	4.7	12	+14.7	S.A.A.O. 1.9m.
HD 204867	GOI	77 IX 19.877	+0.2	8.6	12	+6.7	S.A.A.O. 1.9m.
HD 210934	B8III	77 IX 19.989	-8.7	5.6	7	-5.8	S.A.A.O. 1.9m.

It can be seen that all the stars with standard errors greater than 20km/s are subdwarfs and this reflects the difficulty in measuring the broad lines of these stars. Also many of these stars have only a few lines visible, even at 30A/mm.

No corrections have been made to the velocities of individual lines, such as suggested by Petrie (1953) for HeI λ4026 and HeI λ4471. The Petrie corrections are intended for conventional visual measurement with a long screw measuring machine. When using an oscilloscope line scanning machine much more allowance can be made for blends and any corrections would have to be derived empirically for the various types of star studied, which is not possible from the limited data available. However it is likely that any correction would be smaller than those suggested by Petrie.

More serious problems are encoutered with those sdO stars which have strong Pickering HeII lines in addition to the Balmer lines. If other strong Pickering lines, such as HeII λ4200, were

Table 6.6 Radial Velocities for Northern Stars

Star	Type	Date	R.V.	s.e.	n	FB No.	FB Velocity
HD 264111	B2V	77 III 5.874	+31.4	7.5	9	46	+44,+27 Variable?
BD-3°2179	sdO	77 III 5.897	+103.4	12.1	8		
HD 74721	Ahb	77 III 5.906	+16.1	11.1	4	52	+36
		77 III 6.886	+31.6	3.4	5		
			+23.9	7.8			
GD 298	sdO	77 III 5.923	-38.1	24.8	7	56	-43
		77 III 10.036	-52.9	4.7	8		
			-45.5	10.5			
GD 300	sdO	77 III 6.036	+8.0	14.8	6	60	+17:
F 36	sdB	77 III 10.114	+9.8	61.4	3	69	-48

Star	Type	Date	R.V.	s.e.	n	FB No.	FB Velocity
BD+36°2242	B8:V	77 III 7.015	-10.6	9.6	9	85	-3
HZ 25	B2V	77 III 7.043	+32.9	4.3	8	97	+42
		77 III 9.958	+39.3	4.3	7		
			+36.1	3.2			
F 64	B4:V	77 III 9.967	-170.6	6.7	7		
F 65	Bhb	77 III 6.082	+54.7	11.7	7	101	+55
		77 III 6.974	+20.5	13.5	5		
		77 III 10.171	+42.9	1.5	3		
			+39.4	10.0			
F 66	sdB	77 III 7.059	-15.4	8.8	5	103	-11
(BD+25°2534)		77 III 9.983	+31.6	16.2	5		
			+8.1	23.5			

Star	Type	Date	R.V.	s.e.	n	FB No.	FB Velocity
HD 110166	B7V	77 III 7.070	-77.6	10.9	4	104	-86
F 67	sdO	77 III 10.140	+32.6	38.6	3	106	+22
F 70	B9	77 III 7.090	-1.1	7.8	9	113	-8
(LB 2484)		77 III 9.994	+32.3	8.8	4		
			+15.6	16.7			
HZ 44	sdO	77 III 6.136	-3.1	8.2	8		
		77 III 7.164	+2.5	7.8	8	131	-5
		77 III 10.005	+16.9	13.7	9		
			+5.4	6.0			
HZ 45	Bhb	77 III 6.109	-107.3	16.6	8	132	-124

Star	Type	Date	R.V.	s.e.	n	FB No.	FB Velocity
F 87	sdB	77 III 7.182	+31.9	21.0	4	139	+37
		77 III 10.196	+26.3	4.9	5		
			+29.1	2.8			
F 91	sdB	77 III 10.008	-11.4	10.1	7	143	-57
SA 58-237	sdB	77 III 10.171	+68.7	11.6	3		
TN 209	sdB	77 III 7.199	-5.3	12.9	5	151	-56 Variable?
HD 146813	B1V	77 III 7.151	+20.9	4.9	8	164	+12
		77 III 10.216	+20.0	4.0	10		
			+20.5	0.5			

Table 6.7 Radial Velocities for Southern Stars

Star	Type	Date	R.V.	s.e.	n	Other Velocity	Ref.
SB 290	sdB	77 IX 19.920	-3.9	4.9	4	+52	Graham and Slettebak (1973)
TS 192	sdB	77 IX 19.099	+15.9	12.5	5		
LB 3384	B1.5Ia	77 IX 19.135	+309.3	5.5	8	+306	Feast et al. (1960)
LB 3422	B0Ia	77 IX 20.126	+222.4	7.8	12	+238	Feast et al. (1960)
LB 3459	sdO	77 IX 20.143	+78.2	21.6	3		
HD 165872	B2V	77 IX 18.816	-11.6	9.0	8		
HD 171858	sdB	77 IX 19.754	+8.9	7.2	3		
HD 188112	sdB	77 IX 19.768	+194.9	15.0	2		
JL 82	sdB	77 IX 18.956	+36.0	22.9	3		
HD 205805 (FB 178)	sdB	77 IX 18.776	-76.2	11.2	3	-80	Baschek and Norris (1970)
PHL 178	sdO	77 IX 19.958	+21.0	5.2	6		
PHL 334	sdB	77 IX 19.020	+28.8	24.9	4		
CD-35 15910	sdB	77 IX 19.903	+7.4	4.3	4		

seen and there was any doubt about the correctness of the velocities derived from the Balmer/Pickering lines, these lines were discarded from the velocity determination.

The results in Tables 6.6 and 6.7 show that radial velocities of fair quality can be obtained using 30A/mm image tube spectra. However extensive consideration of galactic motions will not be given here as this would be more appropriate when a larger body of data has been accumulated. An exception has been made in the case of the high velocity stars, HD 188112 and F 64, which are discussed in Section 7.3.

6.5 Balmer Line Widths

Greenstein and Sargent (1974) and Newell (1973) have used the mean widths of the Balmer lines Hγ and Hδ at depths of 10% and 20% of the continuum level (hereafter referred to as D(0.1) and D(0.2)) to determine stellar surface gravities. These methods have been applied to our spectra. The reductions have been performed using the St. Andrews FORTH system which caters for interactive procedures. Most of the FORTH routines used in the reduction process have been developed by Mr. G. Stewart and Mr. P. Bunclark.

a) Scanning the Spectra

All 30A/mm spectra for which calibration plates had been obtained were scanned using the Joyce Loebl microdensitometer of the University Observatory, St. Andrews. The microdensitometer was operated under the control of the FORTH computing system on the

NOVA 820 minicomputer. The basic control routines were those provided by FORTH INC. and extensions written by Mr. J.R. Stapleton. The scanning aperture had a width of approximately 10μ to match the resolution of IIIaJ plates and a height which was as large as the width of the spectrum allowed. A 10μ step was used for the scans.

b) Calibration and Rectification

Since the response of a photographic plate is nonlinear, the plate must be calibrated if the spectral intensity distribution is to be measured. Calibration plates, from the same box of plates as those used for the stellar spectra, were processed with the stellar spectra. The dispersed image of a step wedge illuminated by a quartz iodide lamp was exposed on the plate and also arc lines from a mercury discharge tube to act as a wavelength calibration. A chopper was used in the light path to simulate the intermittency effect associated with trailing the stellar spectrum. The calibration plates were scanned, with the same equipment as the stellar spectra, perpendicular to the wedge steps at 4600A.

The conversion from density, D, to relative intensity, I, has been performed using the linear Baker density, $\log \omega$, (Baker, 1925) which can be represented by the equation

$$\log I = \log A + n \log \omega$$

where $\omega = 10^{D} - 1$, the opacitance, and A is a scale factor. Since only relative intensities are required A is taken to be unity. The value of n is determined from the calibration wedge.

The calibration scans were displayed on the Tektronix 4010 interactive graphics terminal and the cursor used to select the limits of the plate fog and wedge steps. This procedure allows plate defects to be avoided. The mean density for each step was converted to log ω and a linear least squares solution calculated between these values and the known log I values for the wedge. The gradient of the solution gives n. The standard log I values used are listed in Table 6.8 and the derived values of n in Table 6.9 with the number of steps used and the error in n. These values for n are in agreement with those found by Stewart (1978) during an investigation of the behaviour of n with wavelength, exposure, intermittency effects and other photographic effects.

With these values of n the scans of the stellar spectra were converted into relative intensity. The spectra were then rectified by picking off a series of points which represented the continuum and then fitting a spline function to these points. This line was given the value of 1.0 and the data points altered accordingly. The rectification process is the point in the reduction where much of the final error is introduced since the positioning of the continuum is very much a matter of personal judgement. That the process is reasonably successful can be seen from the agreement between the central depths of the Balmer lines measured from different spectra of the same star.

c) Noise and Instrumental Profile Removal using Fourier Techniques

The use of Fourier transforms in astronomy (Brault and White, 1971) for the removal of the effects of noise and the instrumental profile has been extremely well explained by Gray (1976). The basis of the

Table 6.8 Log I Values used for Calibration Wedges

	Log I	
Step	I.N.T.	S.A.A.O.
1	0.000	1.606
2	0.215	1.964
3	0.401	0.164
4	0.581	0.350
5	0.745	0.594
6	0.908	0.772
7	1.055	0.908
8	1.197	1.048
9	1.341	1.181
10	1.475	1.327
11	1.601	1.469
12	1.749	1.605

Table 6.9 Values of the Baker Density Parameter, n

Plate	n	Standard Deviation	No. of Steps
INT 1481A	0.367	0.016	7
INT 1482A	0.327	0.007	7
INT 1483A	0.389	0.014	7
INT 1484A	0.349	0.014	7
INT 1485A	0.380	0.018	7
INT 1486/7A	0.388	0.008	7
INT 1488/9A	0.367	0.016	7
INT 1490A	0.378	0.015	7
INT 1501A	0.417	0.017	7
INT 1502A	0.374	0.015	7
INT 1503A	0.410	0.017	7
CX 1518A	0.369	0.019	7
CX 1519A	0.358	0.015	7
CX 1521A	0.352	0.013	7
CX 1522A	0.377	0.018	7
CX 1523A	0.382	0.024	6

The calibration for CX 1523 is without the highest step which was overexposed.

noise removal technique is that in the frequency domain white noise is present at a constant level for all frequencies but the signal has a cut-off frequency which can be determined by examination of the Fourier transform. The Fourier transforms were obtained using a FORTH routine developed by Mr. G. Stewart from the FORTRAN program given by Gray (1976). A section of the spectrum, consisting of 1024 points and covering both Hγ and Hδ, was transformed and the noise filter was calculated usually with a cut-off between 125 and 150 cycles.

The shape of the instrumental profile was calculated from the arc lines. A unit area Gaussian was fitted to the lines after their profiles had been converted into relative intensity. The best fit was found by trial and error alteration of the width of the Gaussian. Gaussians with standard deviations of 0.22 and 0.27 were found to fit the I.N.T. and S.A.A.O. spectra respectively. The removal of noise and the effect of the instrumental profile was performed in a single deconvolution and the data were then transformed back to the wavelength domain.

d) Line Widths, D(0.2) and D(0.1)

The widths of the Balmer lines were measured for all stars with good comparison spectra since the dispersion at the Balmer lines must be known to convert the line width in Joyce Loebl steps into Ångstroms. The dispersions were calculated from the least squares fits to the comparison arc which were derived in Section 6.4c. The mean dispersions were:-

	for $H\delta$(A/mm)	for $H\gamma$(A/mm)
INT 1481-4	31.655 ± 0.012	31.006 ± 0.007
INT 1486-90	30.853 ± 0.012	29.950 ± 0.015
INT 1501-3	31.671 ± 0.009	31.030 ± 0.010
CX 1518-23	32.508 ± 0.032	31.630 ± 0.030

The widths were measured interactively and where serious blending existed not only the actual width but also an estimated width of the Balmer line alone was measured. In addition the central depth of the lines, R_c, was measured. The mean values of D(0.2), D(0.1) and R_c are given in Table 6.10. Unblended values are given in brackets. For the stars studied by Greenstein and Sargent their values are shown for comparison. The agreement between the values derived here and those given by Greenstein and Sargent can be seen in Fig. 6.1. The three stars which lie furthest from the FB values are F 70 (B9), HZ 45 (Bhb) and HD 146813 (B1V) and if these stars are excluded the least squares fits are

$$D(0.1) = (0.806 \pm 0.117)D(0.1)_{GS} + (2.625 \pm 2.352)$$

$$D(0.2) = (0.831 \pm 0.126)D(0.2)_{GS} + (0.996 \pm 1.472)$$

These fits are shown as dashed lines in the diagram. Since Greenstein and Sargent do not take account of the effect of their instrumental profile and many of their spectra are at a low dispersion, it is expected that their widths would be greater than those derived here. This is indeed the case. The agreement between the central depths is generally very good which suggests that there have been no major differences in the choice of the continuum. Of the three stars

Table 6.10 The D(0.2), D(0.1) and R_c Values

Star	Plate	D(0.2)	D(0.1)	R_c	$D(0.2)_{GS}$	$D(0.1)_{GS}$	R_{GS}
HD 264111	INT 1481e	6.6	11.3	0.36	9.9	16.6	0.47
BD+75 325	INT 1501a	-	12.9	0.19		8	0.17
HD 74721	INT 1481c	23.3	32.3	0.72	23.9	35.5	0.82
GD 299	INT 1482e	6.1	11.6	0.30	5.2	15.1	0.28
	INT 1487b	2.8	13.3	0.26			
F 34	INT 1487a	4.8	9.4	0.31	5.2	11.4	0.30
BD+36 2242	INT 1487e	13.7	23.8	0.44	19.1	28.1	0.66
HZ 25	INT 1488a	8.2	15.1	0.46			
			(11.9)		7.8	14.0	0.45
	INT 1502a	11.1	16.5	0.42			
F 64	INT 1502b	12.4	21.2	0.48			
F 65	INT 1483e	13.8	19.3	0.44	11.4	23.3	0.40
	INT 1487c	9.0	19.3	0.37			
BD+25 2534 (F 66)	INT 1488b	12.0 (7.9)	25.6 (15.6)	0.44	11.5	23.0	0.40
HD 110166	INT 1488c	16.4 (15.5)	26.9 (21.9)	0.62	12.2	19.8	0.58
F 70	INT 1488d	10.2 (8.1)	19.7 (14.6)	0.37	19.4	29.4	0.60
HZ 44	INT 1484b	5.2	15.1 (10.7)	0.33	4.2	13.0	0.32
	INT 1489d	4.7	11.7 (10.0)	0.33			

Star	Plate	D(0.2)	D(0.1)	R_c	$D(0.2)_{GS}$	$D(0.1)_{GS}$	R_{GS}
HZ 45	INT 1484a	6.7	10.5	0.67	15.2	25.6	0.68
F 87	INT 1490a	11.1	22.7	0.46	15.9	25.6	0.49
		(7.9)	(13.7)				
TN 209	INT 1490b	10.1	23.7	0.41	12.6	26.1	0.42
		(8.1)	(14.6)				
HD 146813	INT 1489c	7.6	15.7	0.38	19.1	28.1	0.44
		(7.0)	(10.5)				
SB 290	CX 1522c	19.3	31.7	0.56			
		(16.2)	(24.0)				
LB 3459	CX 1523d	7.9	16.4	0.36			
		-	(14.0)				
HD 149382	CX 1521a	10.4	26.3	0.38			
			(23.4)				
HD 165872	CX 1519a	10.3	16.7	0.45			
		(9.0)	(15.4)				
HD 171858	CX 1521b	17.5	24.7	0.51			
		(15.1)					
HD 188112	CX 1522c	30.3	42.1	0.62			
JL 82	CX 1519e	14.8	24.1	0.44			
		(11.1)	(18.8)				
HD 205805	CX 1518c	20.2	29.6	0.57			
		(16.5)	(24.2)				
PHL 178	CX 1522d	-	11.4	0.19			
CD-35 15910	CX 1522b	16.0	27.4	0.52			
		(13.3)					

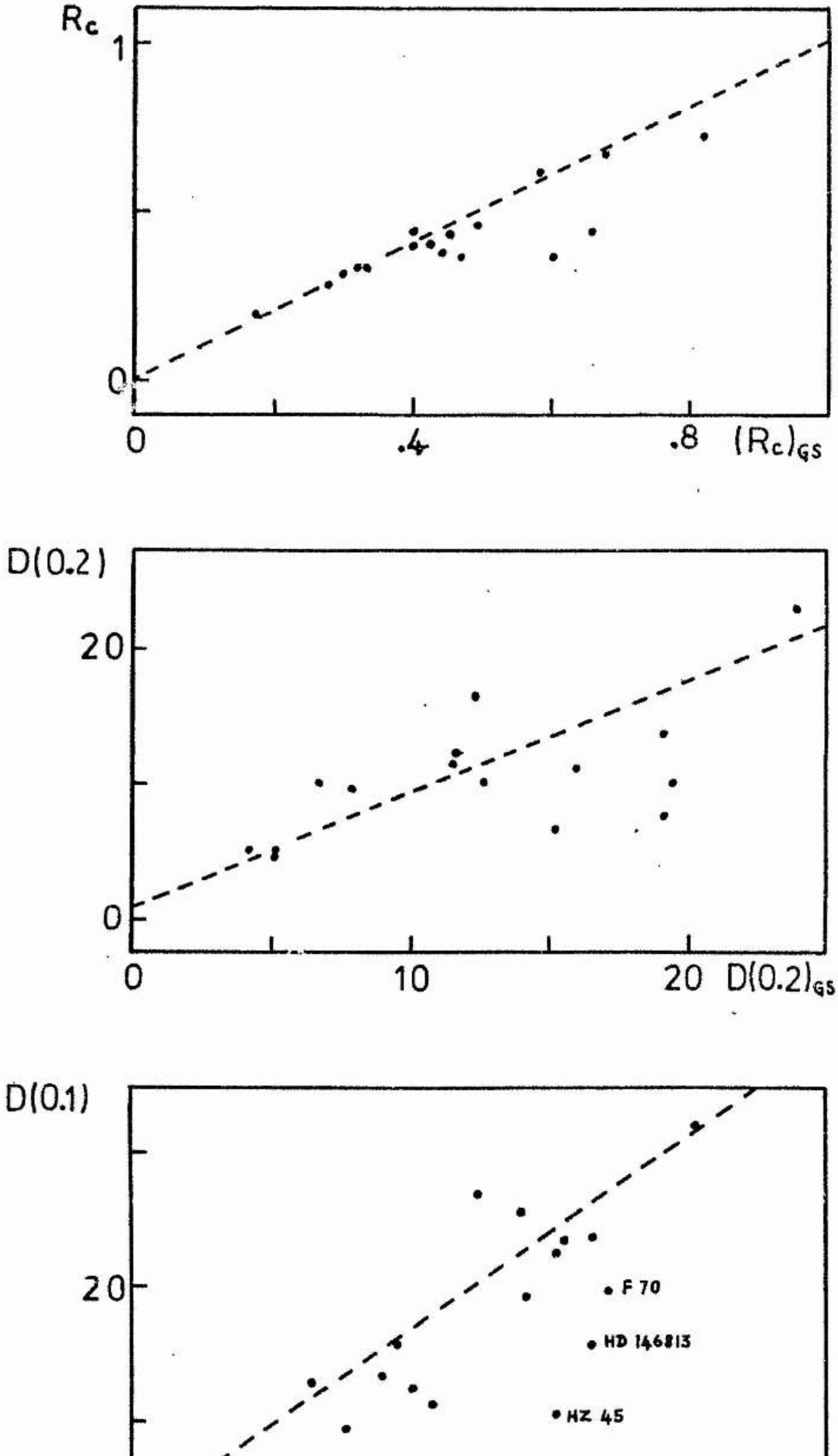


Figure 6.1 Comparison with the Line Measurements of Greenstein and Sargent (1974)

mentioned above only F 70 lies far from the 45° line in the R_c diagram. BD+36°2242 has a large difference in R_c but its widths agree reasonably well.

The derived values of D(0.2) and D(0.1) will be used in the next chapter to determine log g values using the Greenstein and Sargent grid of models.

CHAPTER 7

PHYSICAL PROPERTIES OF FAINT BLUE STARS

The observations and results discussed in the previous chapters are now used to derive physical properties for these stars and show the value of the observational methods.

7.1 Effective Temperature

Effective temperatures have been determined from Strömgren colours for those stars with $-0.1 < [u-b] < 1.4$. The reddening-free parameter $[u-b]$ has been used as a temperature indicator by Osmer and Peterson (1974) and Philip and Newell (1975) with calibrations based on model atmosphere calculations. The values of $E(u-b)/E(b-y)$ adopted for these calibrations were 1.84 and 1.61 respectively. However Shobbrock (1976) has shown that the ratio $E(u-b)/E(b-y)$ is variable from a comparison of stars in Sco OB1, h and χ Per and upper Centaurus. Davis and Shobbrock (1977) have used this finding in conjunction with the empirical temperature scale of Code et al. (1976) to derive a temperature calibration for c_o and $[u-b]$. Davis and Shobbrock prefer the c_o index since it is only slightly affected by changes in the adopted reddening relations. Unfortunately, since intrinsic colours for faint blue stars are uncertain, the Davis and Shobbrock $[u-b]$ calibration with a mean $E(u-b)/E(b-y)$ value of 1.6 has had to be used in preference to the c_o calibration. Supergiants lie on a different $[u-b] - \theta$ locus from stars of luminosity classes III - V but supergiants would not normally be found in a sample of faint blue stars. It will be assumed, as proposed by Philip and Newell, that subdwarfs follow the same [u-b] - T_{eff} relationship as dwarfs.

Temperatures have been derived using all three calibrations with the appropriate E(u-b)/E(b-y) ratios and restrictions. The stars considered were those for which line widths or the number of Balmer lines were calculated in Chapter 6. The [u-b] values for these stars have been determined from the photometry given by Kilkenny and Hill (1975), Kilkenny et al. (1977), Kilkenny (1977) and Graham (1970). Temperatures were also found for the appropriate stars which have Strömgren photometry in Chapter 3.

The derived and mean values of θ ($\theta = 5040/T$) are given in Table 7.1. The numbers in the 'Ref.' column indicate values from

(1) Greenstein and Sargent (1974)

(2) Newell (1973)

(3) Baschek and Norris (1975)

(4) Baschek and Norris (1970)

Spectroscopic classifications are quoted in preference to photometric classifications when available. The individual determinations of θ are identified by the initials of the authors of the method. The differences between θ(PN) and the θ values from the Osmer and Peterson and Davis and Shobbrock methods are plotted against θ(PN) in Fig. 7.1 with the θ(DS) values as crosses and θ(OP) values as dots. Clearly the values from the Osmer and Peterson calibration and that of Davis and Shobbrock are related with $\theta(OP) \approx \theta(DS) + 0.12$. The Philip and Newell calibration appears to be in reasonable agreement with that of Osmer and Peterson for the hotter stars but

Table 7.1 θ (=5040/T) Values determined using Three Different Calibrations

Star	Type	θ(PN)	θ(OP)	θ(DS)	$\bar{\theta}$	Published θ values	Ref.
LB 3130	Ahb	0.468	0.492	-	0.480	0.50	(2)
BD-15°115	B3V	0.255	0.249	0.262	0.255		
TS 192	sdB	0.241	0.238	0.250	0.243	0.18	(2)
TS 195	B3(sd?)	0.296	0.290	0.305	0.297	0.28	(2)
HD 15910	B8-9V	(0.419)	0.447	0.455	0.451		
PHL 1434	B2(sd?)	0.275	0.267	0.281	0.274		
F 30	B5V	0.325	0.326	0.343	0.331		
LB 1652	A0	(0.477)	0.503	-	0.503		
PHL 1548	sdB	0.160	0.163	0.172	0.165		
TS 401	B6(Binary?)	0.342	0.350	0.363	0.352		
BD-13°842	sdOp,DOp	0.224	0.231	0.234	0.230		
LB 1735	B4V	0.299	0.293	0.309	0.300		
LB 3459	sdO	-	0.140	0.150	0.145		
HD 76431	sdO,DO	0.169	0.172	0.182	0.174		

Star	Type	θ(PN)	θ(OP)	θ(DS)	$\bar{\theta}$	Published θ values	Ref.
BD-2°3766	B1	0.222	0.218	0.233	0.224		
HD 125924	B1.5	0.225	0.221	0.235	0.227	0.24	(1)
BD-9°4395	H-poor B	0.156	0.144	0.169	0.156		
HD 149382	sdB	0.167	0.170	0.180	0.172	0.126	(3)
HD 150055	A0V	(0.478)	0.492	-	0.492		
HD 165872	B2V	0.183	0.163	0.194	0.180	0.19	(2)
HD 171858	sdB	0.193	0.193	0.205	0.197		
JL 6	B2(sd?)	0.310	0.311	0.323	0.315		
HD 188112	sdB	0.256	0.252	0.263	0.257		
JL 36	B1	0.211	0.205	0.223	0.213		
JL 62	B5	0.306	0.299	0.318	0.308		
PHL 1580	sdB	0.192	0.190	0.204	0.195		
JL 82	sdB	0.214	0.212	0.226	0.217		
PHL 44	sdB	0.208	0.207	0.219	0.211		
PHL 48	B2	0.230	0.225	0.236	0.230		

Star	Type	θ(PN)	θ(OP)	θ(DS)	$\bar{\theta}$	Published θ values	Ref.
HD 205805	sdB	0.209	0.208	0.220	0.212	0.21,0.20,0.19	(1,2,4)
PHL 4748	Ahb	(0.468)	0.494	-	0.494		
PHL 110	B9	(0.405)	0.427	-	0.427		
JL 87	B0(sd?)	0.187	0.182	0.197	0.189		
PHL 159	B1.5	0.243	0.236	0.252	0.244		
PHL 227	B1	0.216	0.204	0.221	0.214		
LB 1502	B9	(0.410)	0.437	-	0.424		
PHL 1957	B9.5(hb?)	(0.448)	0.473	-	0.473		
HD 213728	B7V	0.350	0.357	0.373	0.360		
HD 213781	B7V	0.339	0.342	0.359	0.347		
PHL 334	sdB	0.155	0.159	0.168	0.161	0.15	(2)
PHL 5382	B7	(0.362)	0.375	0.388	0.382		
PHL 375	B7(sd?)	(0.378)	0.394	0.406	0.400		
JL 124	sdB	0.214	0.205	0.226	0.215		
PHL 460	B5	0.319	0.319	0.334	0.324		

Star	Type	θ(PN)	θ(OP)	θ(DS)	$\bar{\theta}$	Published θ values	Ref.
CD-35°15910	sdB	0.197	0.197	0.208	0.201		
PHL 610	sdB,DB	0.140	0.147	0.161	0.149		
HD 264111	B2V	0.208	0.193	0.220	0.207	0.23	(1)
BD+6°2461	B2V	0.195	0.194	0.206	0.198	0.21	(1)
BD+36°2242	B8:V	(0.403)	0.426	0.434	0.430	0.43	(1,2)
HZ 25	B2V	0.252	0.246	0.259	0.252	0.26	(1)
F 64	B4:V	0.318	0.319	0.335	0.324		
F 65	Bhb	0.212	0.210	0.223	0.215	0.19,0.20	(1,2)
F 66	sdB	0.165	0.169	0.170	0.168	0.18	(1,2)
HD 110166	B7V	(0.374)	0.398	0.401	0.400	0.39	(1)
F 70	B9	(0.439)	0.465	-	0.465	0.48,0.47	(1,2)
HZ 44	sdO	-	0.138	0.148	0.143	0.13,0.14	(1,2)
HZ 45	Bhb	0.332	0.338	0.351	0.340	0.33	(1,2)
F 87	sdB	0.187	0.174	0.198	0.186	0.18	(1)
HD 146813	B1V	0.227	0.223	0.237	0.229	0.22	(1)

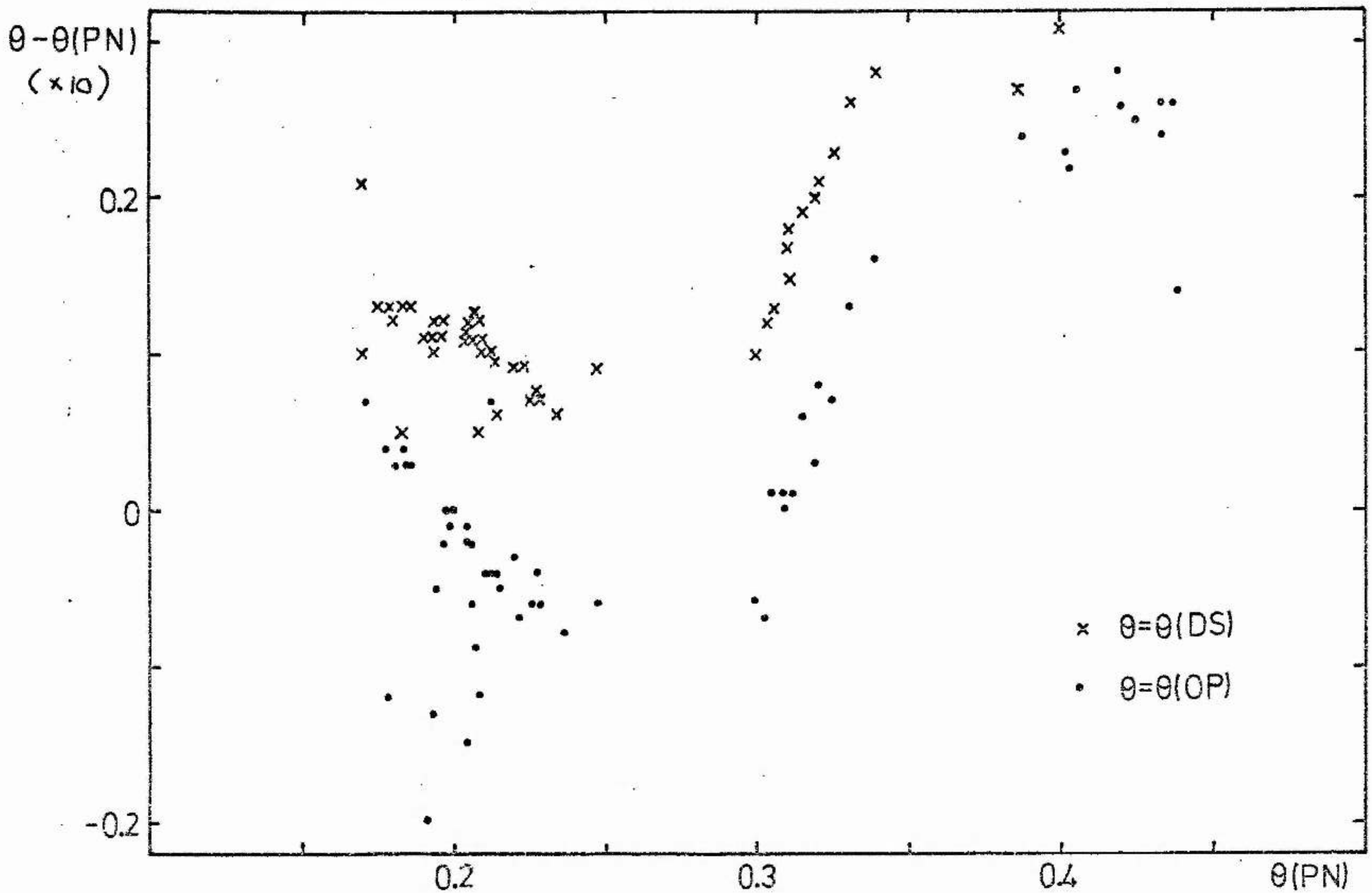


Figure 7.1 The Behaviour of the Osmer-Peterson and Davis-Shobbrock θ Values when compared with the Philip-Newell Calibration

diverges for $\theta > 0.35$.

Relyea and Kurucz (1978) give theoretical Strömgren colours for a large grid of LTE model atmospheres. Although no attempt has been made to obtain a $[u-b] - \theta$ calibration from this data, the behaviour of $[u-b]$ with θ was investigated to see how well it agreed with the calibrations used earlier. The agreement between the theoretical $[u-b]$ values for $3.0 < \log g < 4.5$ and the Davis and Shobbrock calibration was excellent. However, as suspected from Fig. 7.1, the Philip and Newell calibration undervalues θ by at least 0.02 for $\theta > 0.35$. Hence the Philip and Newell calibration was only used in the determination of mean θ values when $\theta \leq 0.35$. The standard errors in the mean θ values average 0.005 and 0.006 for three and two determinations of θ respectively. Thus the mean internal error for three determinations corresponds to an error in temperature of 275, 630 and 1120 K at $\theta = 0.3$, 0.2 and 0.15 respectively.

An estimate of the overall errors in the θ determination may be found from a comparison with the previously published values given in Table 7.1. The mean residual in the sense (derived - previously published) is $+0.005 \pm 0.005$(s.e.) . When compared with the Greenstein and Sargent (GS) and Newell values separately, the mean residuals are -0.001 ± 0.004(s.e.) and $+0.007 \pm 0.006$(s.e.) respectively. From these figures it is clear that there are no large systematic differences between the mean θ values derived here and previous temperature estimates for faint blue stars. Thus the overall error in θ will be of the order of ± 0.01.

Unfortunately for some sdO stars, notably F 34 and GD 299, [u-b] is too negative to allow determination of θ. However any temperature determination for such stars which does not allow for NLTE effects is very doubtful.

7.2 Surface Gravity

The technique of Greenstein and Sargent (1974), which uses the D(0.2) widths of $H\delta$ and $H\gamma$ to calculate log g, was applied to those stars in Table 6.10 for which the determination of θ was possible. Greenstein and Sargent used an array of model atmosphere calculations to calibrate log D(0.2) in terms of θ and log g. The relationships used are of the form

$$\log D(0.2) = 0.2 \log g + C(\theta)$$

The log g values are given in Table 7.2 and were estimated directly from Figure 3 of Greenstein and Sargent using the appropriate values of θ and D(0.2). The values given in brackets should be the more accurate since they are calculated from line widths which were corrected for blends.

When the results are compared with those of Greenstein and Sargent (1974) and Newell (1973), it can be seen that the line widths produce surface gravities which are systematically smaller than those by either author. The mean difference between the values given in Table 7.2 and the corresponding GS values is -0.2 ± 0.5(s.d.) and probably reflects the correction for instrumental profile and blends in our work. Excluded from this calculation were F 70 and HZ 45 about which comments are made in Section 6.5d. The equivalent figure for the Newell values is -0.3 ± 0.6(s.d.) . For comparison

Table 7.2 Log g using Balmer Line Widths

Star	Type	Log D(0.2)	θ	Log g
HD 264111	B2V	0.820	0.21	3.6
BD+36° 2242	B8:V	1.137	0.43	3.4
HZ 25	B2V	0.987	0.25	3.9
F 64	B4:V	1.093	0.32	3.8
F 65	Bhb	1.057	0.21	4.6
F 66	sdB	1.079 (0.898)	0.17	5.3 (4.5)
HD 110166	B7V	1.215 (1.190)	0.40	3.9 (3.8)
F 70	B9	1.009 (0.908)	0.47	2.8 (2.5)
HZ 44	sdO	0.699	0.14	4.5:
HZ 45	Bhb	0.826	0.34	2.8:
F 87	sdB	1.045 (0.898)	0.19	5.1 (4.5)
HD 146813	B1V	0.881 (0.845)	0.23	3.7:(3.6:)
LB 3459	sdO	0.898	0.15	5.1:
HD 149382	sdB	1.017	0.17	4.9
HD 165872	B2V	1.013 (0.954)	0.18	4.7 (4.3:)
HD 171858	sdB	1.243 (1.179)	0.20	5.5 (5.2)
HD 188112	sdB	1.481	0.26	6.2
JL 82	sdB	1.170 (1.045)	0.22	4.8 (4.4)
HD 205805	sdB	1.305 (1.217)	0.21	5.7 (5.2)
CD-35° 15910	sdB	1.204 (1.185)	0.20	5.3 (5.2)

the mean difference between the GS and Newell values for the same stars is $+0.3 \pm 0.3$(s.d.) . From Table 3 of Greenstein and Sargent it is clear that errors in log g of 0.5 can easily be introduced from the determination of D(0.2) and the error in the log g values in Table 7.2 will be at least of this order.

A log g - log T_{eff} diagram has been plotted in Fig. 7.2 and also shows the Newell (1973) classification zones. Newell examined the connection between these zones and the evolutionary tracks for horizontal branch stars. Zone A corresponds to conventional horizontal branch stars which have evolved from red giants. Zone BC also contains true horizontal branch stars in that they have evolved from red giants and have the same internal energy structure. However these stars have lower masses, 0.5 - 0.55 $M_\odot$, than the stars in zone A. These masses are too small to allow the stars to follow the asymptotic giant branch and the stars evolve bluewards to become white dwarfs. The stars in zone HL are thought to be a combination of evolved zone A stars and stars evolving directly from red giants to become white dwarfs. Newell could not explain zone D by evolution tracks. This zone contains the sdB stars and seems likely to be connected with blue horizontal branch evolution.

The stars in common with Newell's work are mostly in zone D and are often shifted to slightly lower log g. Most of the stars fall in the zones and although HD 110166 (B7V) falls in the Newell Gap 1 this star would appear to be of Population I rather than a horizontal branch star.

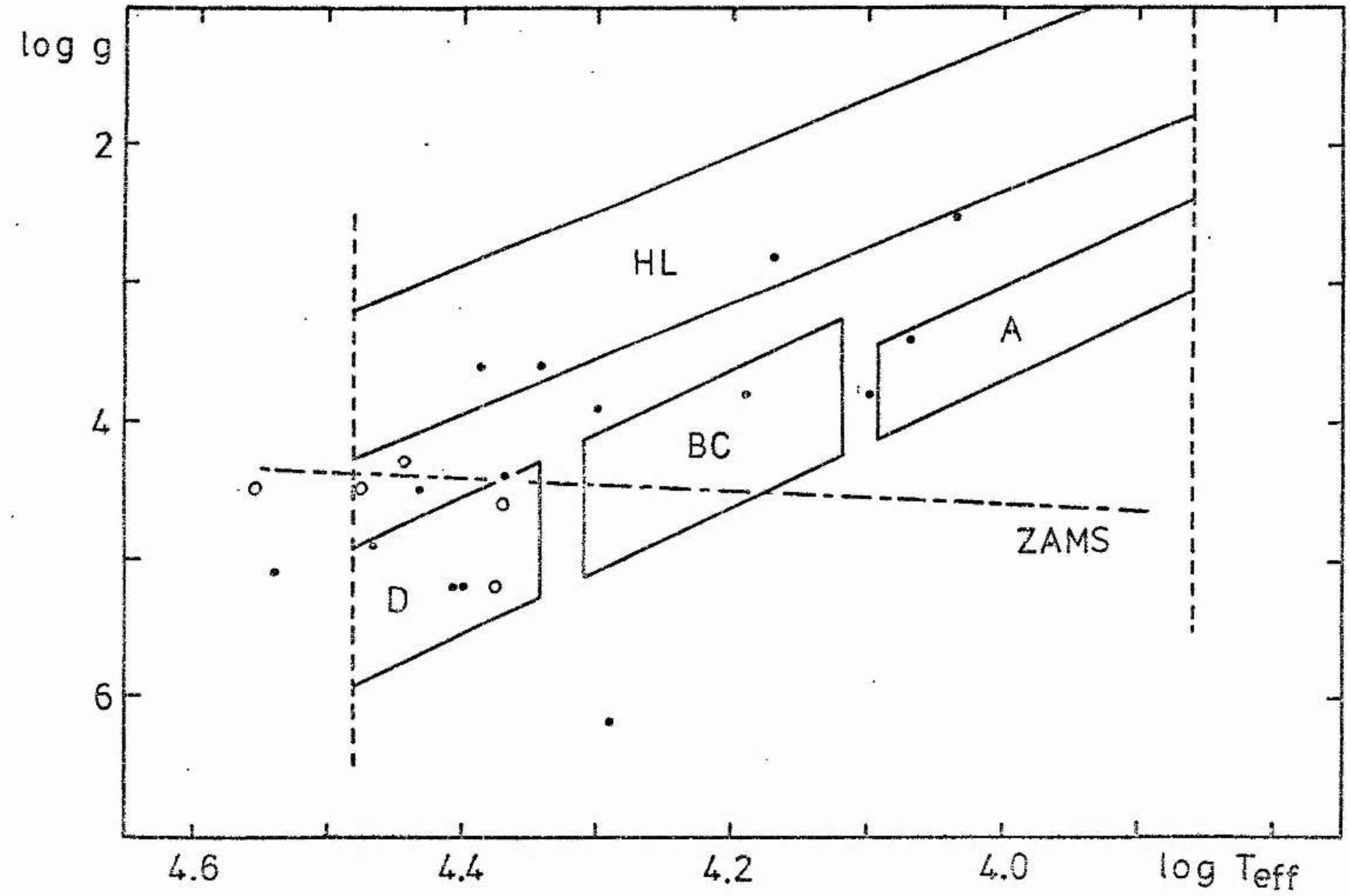


Figure 7.2   Log g - Log T_{eff} Diagram with Newell Classification Zones

Open circles denote stars which have also been observed by Newell.

7.3 Absolute Magnitudes, Kinematics and Some Evolutionary Implications

The relationship between [38-b] and the Hβ index, given in Section 4.7, has been used with the Crawford (1978) β - M_V calibration to obtain absolute magnitudes for those stars in Table 4.4 classified as normal B dwarfs from Strömgren photometry. The formula

$$\beta' = 0.383[38\text{-}b] + 2.431 ,$$

derived from stars of luminosity classes I - V, was used. Allowance was made for interstellar absorption using the Crawford ratio of total to selective absorption, $A_V = 4.3\ E(b-y)$. The $E(b-y)$ values were obtained from the c_1 - $(b-y)$ diagram (Figure 3.6). Photometric spectral types were also used to estimate absolute magnitudes using the values given by Crawford (1978) for MK spectral types. Absolute magnitudes and distances are given in Table 7.3. The table is arranged as follows:-

Column	
1	The star name.
2	The photometric spectral type.
3	[38-b].
4	The Hβ index derived from [38-b], β'.
5	The interstellar absorption, A_V.
6	The absolute magnitude derived from β', M_V'.
7	The distance derived from M_V', d.
8	The absolute magnitude derived from the spectral type, $M_V(MK)$.

Table 7.3 Absolute Magnitudes and Distances using [38-b] and the Crawford β-M_V Calibration

Star	Type	[38-b]	β'	A_V	M'_V	d(kpc)	M_V(MK)	d_{MK}	r(kpc)	z(kpc)
JL 87	B0(sd?)	0.448	2.602	0.4	-4.0	13.5	-3.8	12.3	10.9	-8.0
BD-2°3766	B1	0.495	2.620	0.1	-3.2	4.7	-3.7	5.9	2.6	+3.9
JL 36	B1	0.497	2.621	0.3	-3.1	14.5	-3.7	18.6	12.4	-7.5
PHL 1580	B1	0.392	2.581	0.2	-5.2	29.4	-3.7	14.8	21.3	-20.2
PHL 227	B1	0.502	2.623	0.7	-3.0	14.5	-3.7	19.3	10.5	-9.9
HD 125924	B1.5	0.530	2.633	0.1	-2.6	2.8	-2.6	2.8	1.9	+2.1
PHL 159	B1.5	0.533	2.635	0.1	-2.6	4.4	-2.6	4.5	3.5	-2.7
HD 188112	B1.5(sd?)	0.666	2.685	0.0	-1.0	1.8	-2.6	3.7	1.6	-0.75
PHL 1434	B2(sd?)	0.665	2.685	0.0	-1.0	5.2	-2.2	8.8	2.3	-4.6
PHL 48	B2	0.557	2.644	0.0	-2.2	13.8	-2.2	13.4	10.6	-8.8
TS 195	B3(sd?)	0.669	2.687	0.0	-1.0	4.1	-1.1	4.4	0.51	-4.1
JL 62	B5	0.608	2.663	0.2	-1.6	3.6	-0.6	2.3	3.0	-2.0
PHL 460	B5	0.732	2.711	0.0	-0.4	3.4	-0.6	3.7	1.3	-3.2

Star	Type	[38-b]	β'	A_V	M'_V	d(kpc)	M_V(MK)	d_{MK}	r(kpc)	z(kpc)
TS 401	B6(Binary?)	0.740	2.714	0.0	-0.4	3.4	-0.3	3.4	2.4	-2.5
PHL 5382	B7	0.818	2.743	0.0	+0.1	3.1	-0.2	3.5	1.5	-2.7
PHL 375	B7(sd?)	0.906	2.777	0.1	+0.5	1.9	-0.2	2.5	1.3	-1.4
PHL 110	B9	0.841	2.752	0.2	+0.2	3.4	+0.6	2.8	2.5	-2.3
LB 1502	B9	0.853	2.757	0.0	+0.3	3.6	+0.6	3.0	2.0	-3.0
PHL 1957	B9.5(hb?)	0.857	2.758	0.2	+0.3	2.0	+0.9	1.5	1.3	-1.5
HD 150055	B9.5	1.102	2.852	0.9	+1.0	0.62	+0.9	0.67	0.62	+0.07
LB 1652	A0	0.998	2.812	0.1	+0.8	2.1	+1.1	1.8	1.2	-1.8

9 The distance derived from $M_V(MK)$, d_{MK}.

10 The projection of d on the galactic plane, r.

11 The distance above the galactic plane, z.

Since the error in a single [38-b] value is ± 0.023, the error expected in M_V from the transformation to β' varies from 0.4 at B0 to 0.2 at B5 and 0.15 at B9 with a corresponding effect on the distances. From Table 7.3 it is clear that certain stars, notably PHL 1580, which has an unusually small [38-b] value, PHL 227, PHL 48 and JL 87, are at excessive distances from the galactic plane if they are normal dwarfs.

An initial check on the likelyhood of a star being subluminous is provided by its proper motions. Faint B dwarfs would be expected to show small or zero proper motions for any reasonable tangential velocity. However when the errors become comparable with the proper motion, usually when $\mu < 0''.006$ for Luyten proper motions, the derived tangential velocity is unreliable. Those faint blue stars, which have been classified as sdB, sdO or normal B stars from Strömgren photometry and have published proper motions, were considered. Proper motions have been taken from Luyten (1969) unless otherwise stated.

The sample of sdB stars with published proper motions totals 23 stars. The mean absolute magnitude for these stars may be estimated from their reduced proper motions, $H = m_V + 5 \log \mu$, where m_V is the apparent magnitude and μ the total proper motion. Greenstein and Sargent (1974) give the approximate formula

$$\overline{M}_V = \overline{H} + 6.23 - 5 \log \sigma'(\rho) ,$$

where $\sigma'(\rho)$ is the dispersion in radial velocity and a bar indicates a mean. $\sigma'(\rho)$ was estimated as 42 by Greenstein and Sargent for their sample of stars. For the 23 sdB stars $\overline{H}$ is 4.7 ± 0.4(s.e.) and hence the mean absolute magnitude is +2.8. This is comparable with the mean values of +3 assumed by Baschek and Norris (1975) and +3.2 derived by Greenstein and Sargent. Thus distances were calculated assuming an absolute magnitude of +3 and then used to derive the transverse velocity components T_α and T_δ. The total proper motions, distances and transverse velocities are given in Table 7.4. Galactic velocity components have been given by Baschek and Norris for 11 stars in Table 7.4, and showed that a substantial number of sdB stars have evolved from the old disc population rather than the halo population. Among the stars in Table 7.4 not discussed by Baschek and Norris are several which appear to have large space velocities including PHL 717, PHL 3802, PHL 197 and F 48. However F 48 has large errors for its proper motions. Unfortunately radial velocities are not available for these stars. It may be significant that these stars are among the fainter objects studied and may be intrinsically fainter than other sdB stars.

A similar process can be applied to the sdO stars although this is more complicated due to their larger spread in absolute magnitude. Using reduced proper motions, $\overline{H}$ is 5.0 ± 0.6(s.e.) for 13 stars and $\sigma'(\rho)$ is 55km/s from Greenstein and Sargent. This leads to a mean absolute magnitude of +2.5 while the stars studied by Greenstein and Sargent have a mean absolute magnitude of +3.2. However, as can be seen in Fig. 3 of Kilkenny, Penfold and Hilditch (1978), sdO stars occur between absolute magnitudes of +6 and 0

Table 7.4 Transverse Velocities for sdB Stars

Star	μ (")	r(pc)	T_α(km/s)	T_δ(km/s)
PHL 717	0.022	2005	181	105
LB 1559	0.033	752	108	-51
HD 4539	0.040	288	45	30
PHL 6783	0.029	437	-8	-60
F 11	0.034	640	61	-82
PHL 1003	0.021	1081	108	5
LB 3187	0.010	855	-16	-37
PHL 1126	0.103	565	276	-19
F 14	0.027	916	96	-65
PHL 3802	0.092	738	297	-122
F 36	0.021	904	-73	51
F 38	0.008	1014	-38	5
F 48	0.034	1236	-152	-129
HZ 22	0.011	1047	-5	-55
F 65	0.015	634	36	-27
F 66	0.020	324	-5	-31
F 81	0.036	1276	200	-91
F 91	0.060	1259	-310	179
HD 149382	0.027	155	-18	-7
PHL 17	0.023	1563	-89	-148
HD 205805	0.085	275	110	-13
PHL 197	0.052	1294	117	295
LB 1516	0.031	986	112	94

Table 7.5 Transverse Velocities for sdO Stars

	$M_V = +2.5$			$M_V = +5$		
Star	r(pc)	T_α	T_δ	r(pc)	T_α	T_δ
F 20	1854	457	-228	586	145	-72
F 26	2089	188	69	661	60	22
F 34	550	87	-63	174	28	-20
F 46	1445	-370	302	457	-117	95
LB 2197	1637	-23	-279	518	-7	-88
BD+18 2647	745	-28	-113	236	-9	-36
HZ 44	695	-204	102	220	-65	32
LB 1566	1337	-63	32	423	-20	10
PHL 829	718	-31	-24	227	-10	-8
LB 3241	1112	63	179	352	20	57
LB 3459	542	-28	167	171	-9	53
PHL 464	738	11	-11	233	3	-3
LB 1526	1556	-162	-243	492	-51	-77

and may extend to -2. Most are confined to the range +5 to +2 and absolute magnitudes of +2.5 and +5 have been used to calculate distances and transverse velocities which are given in Table 7.5. Few of these stars seem to show high velocities.

Galactic orbits have been calculated for the more interesting subdwarfs and main-sequence stars. The computer program used was written by Dr. F. House, Ruhr-Universität, Bochum and was kindly supplied by Dr. D. Kilkenny. The Schmidt (1965) model of the galaxy is used. The properties of the model are determined from the observed galactic rotation curve. The model consists of three components: a point mass of $0.7 \times 10^{10}\ M_\odot$ at the galactic centre; an oblate spheroid of eccentricity 0.812, radius 10kpc and mass 8.2×10^{10} $M_\odot$; and a shell beyond 10kpc with a mass of $9.3 \times 10^{10} M_\odot$. The total mass is thus $1.8 \times 10^{11} M_\odot$. The radial density distribution is

$$\rho(r) = 3.93\ r^{-1} + 0.02489\ r \qquad \text{for the spheroid}$$

and $$\rho(r) = 1449.2\ r^{-4} \qquad \text{for the shell.}$$

The orbits were calculated stepwise backwards in time through the gravitational field of the Schmidt model from the present positions and motions of the stars.

Eight of the thirteen subdwarfs considered were found to have bound orbits. Table 7.6 gives the parameters of these orbits and contains the star name, radial velocity, maximum and minimum radial distances, period of the radial motion and the extent and period of the z motion. The stars are discussed individually in order to outline the special characteristics of each case.

HD 171858

The proper motions for this sdB, $\mu_\alpha \cos\delta = -0\overset{''}{.}001$ and $\mu_\delta = -0\overset{''}{.}007$,

Table 7.6 Bound Galactic Orbits of Subdwarf Stars

Star	R.V.	R_{Min}	R_{Max}	$P_R(10^8 yr)$	z	$P_z(10^8 yr)$
HD 171858	+9	9.76	10.57	2	0.055	0.7
F 64	-171	1.1	10.3	1.3	3	1.05
HD 125924	+252	5.5	23	4.3	See Text	
HD 165872	-12	2.2	10.0	1.2	1.8	0.8
F 48	-75	1.6	11.2	1.2		
	-50	1.8	11.5	1.3	See Text	
	0	2.4	12.3	1.45		
	+75	3.4	14.8	1.95		
PHL 3802	-75	0.1	10.1	2.0		
	-50	0.2	10.1	1.25		
	0	0.3	12.8	1.4	See Text	
	+50	0.4	12.1	1.4		
	+75	0.4	13.1	1.4		
	+100	0.5	13.1	1.4		
LB 3459	+78	6.6	10.1	1.5	0.525	0.64
PHL 1126	+101	1.6	17.4	2.1	See Text	

were taken from the SAO Star Catalogue (Smithsonian Institution, 1966). The orbit is much less eccentric than those found for other sdB stars. This suggests that HD 171858 may have evolved from a Population I star whose kinematic properties are not dissimilar to that of the sun.

F 64

This star was classified as B4:V in Section 6.3. However if a main sequence luminosity is assumed the orbit is not bound and the star crosses the galactic plane only once. This occurs at t = 56.6 x 10^6 years and r = 55.9kpc. t is measured backwards in ti·e. At this point the u and w velocity components would have been +992 and -93 km/s. This seems unlikely since the main sequence lifetime of a B4 star is of the order of 3×10^7 years (Iben, 1967) and it is doubtful whether young stars would be present 56kpc from the galactic centre. If the star is assumed to be subluminous a bound orbit is found with a form similar to that found for other subdwarfs.

HD 125924

This star was considered unlikely to be a normal B star by Hill (1968) due to its space motion, while Berger et al. (1971) thought the star to be normal but ejected from the galactic plane. Greenstein and Sargent (1974) also considered it normal. If the distance given in Table 7.3, which assumes the star to be normal, is used the resultant orbit is not bound and never crosses the galactic plane. The only explanation for this would be that the star formed more than 2.3kpc from the galactic plane with a large space velocity. If the star is considered to be a subdwarf a bound highly eccentric orbit is found.

The orbit has crossed the galactic plane only three times in the past 5×10^8 years. The most recent crossing was 10^6 years ago when r, u and w were 10.04kpc, +177km/s and -165km/s. The other crossings occurred 3.5×10^8 and 4.2×10^8 years ago. It seems most likely that this star was ejected from the galactic plane approximately 10^6 years ago.

HD 165872

Newell (1973) placed this star in his HL group of stars evolving from the asymptotic giant branch towards the sdO stars. While a spectral classification of B2V was given in Section 6.2, Strömgren photometry (Kilkenny, Hill and Brown, 1977) suggests the star is subluminous. Although the radial velocity is only -12km/s the proper motion is large, $-0\overset{''}{.}152$ and $-0\overset{''}{.}099$ in α and δ. If the star is assumed to be on the main sequence the derived orbit is not bound and never crosses the galactic plane. However with an absolute magnitude of +3 a bound orbit is found.

F 48

Since no radial velocity is available for this sdB star a range of radial velocities was used. The orbits are bound for radial velocities between -75km/s and +75km/s. The radial motion is highly eccentric and the z oscillations are of medium amplitude. The star goes further than 2kpc from the galactic plane only in the +75km/s case. The orbits for radial velocities of 0km/s and -75km/s are shown in Figure 7.3 as typical examples of the bound orbits found for sdB stars. The points are spaced at intervals of approximately 5×10^6 years.

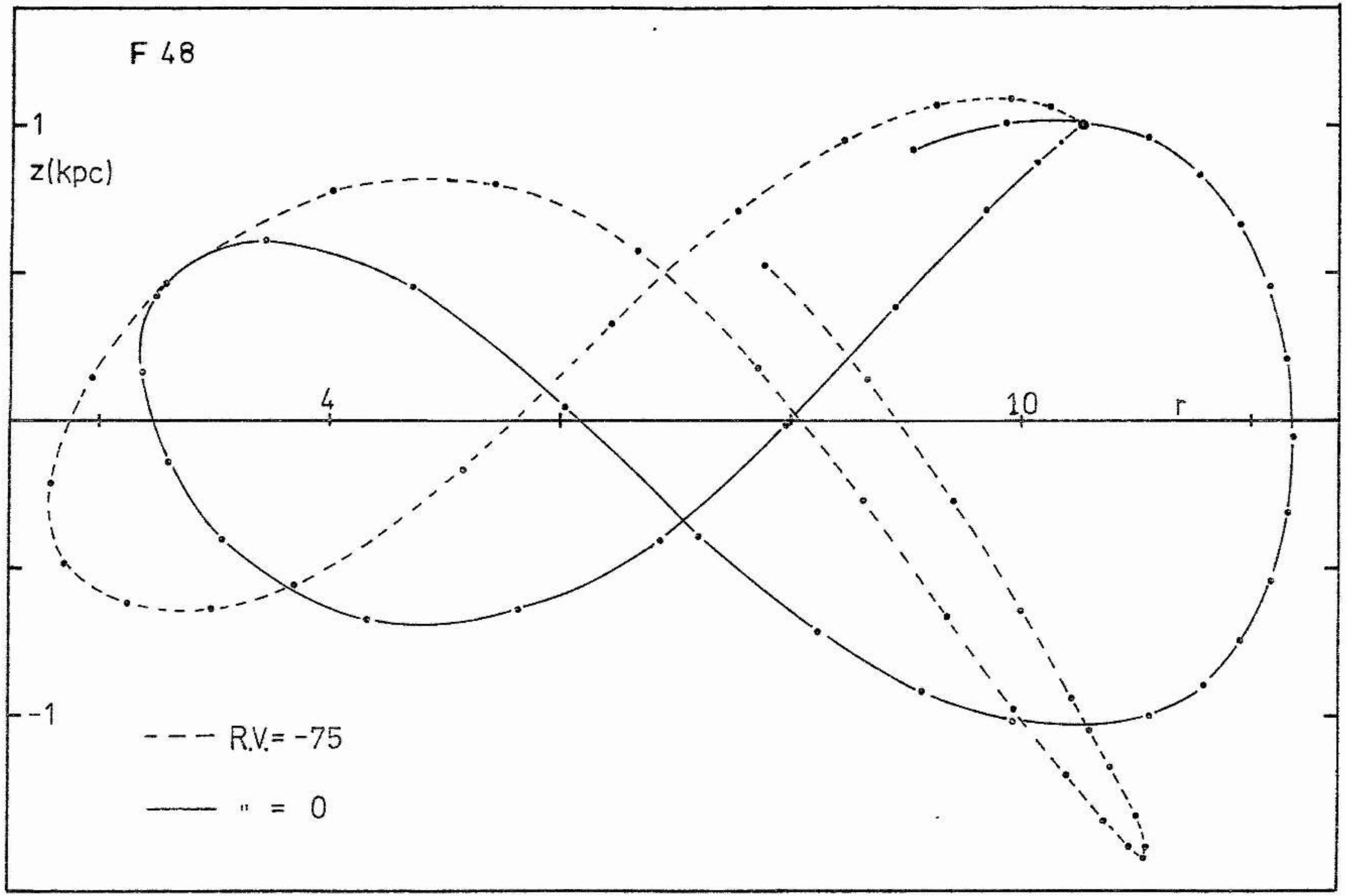


Figure 7.3 The Orbits of F 48 over the past 1.5×10^8 Years

PHL 3802

This sdB star has no published radial velocity and values from -75km/s to +100km/s were assumed for the orbit calculations. The orbits are similar to those of F 48, except that they pass very close to the galactic centre. The z motion is increased as more negative radial velocities are considered. From the behaviour of the orbits it seems unlikely that the radial velocity would be outside the range ±50km/s. It is possible that this star has been ejected from the galactic plane, rather than following this very eccentric type of orbit taking it close to the galactic centre.

PHL 1126

This sdB star has a very large radial oscillation of approximately 16 kpc but the oscillation perpendicular to the galactic plane has a low amplitude. The orbit rarely reaches more than 1 kpc from the galactic plane.

LB 3459

This eclipsing binary system has a period of $0^{d}.2615$ and consists of an sdO and a hot white dwarf. (Kilkenny, Hilditch and Penfold, 1978; Kilkenny, Penfold and Hilditch, 1978). The orbit is less eccentric than those found for sdB stars with the exception of HD 171858. This suggests that this system is younger than the majority of sdB stars.

A further group of five subdwarfs was found to have no bound orbit. From the orbits calculated it appears that the stars have come from very large distances outside the galaxy and have passed through the galactic plane to reach their present positions. It seems much more likely that the stars have been ejected from the galactic plane with large velocities. This ejection generally seems to have occurred between 10^6 and 10^8 years ago. The five stars are discussed below.

HD 188112

This star was classified as sdB in Section 6.3 and although Strömgren photometry gives a classification of B1.5(sd?) it seems very likely that the star is subluminous. The orbit derived for a main sequence luminosity crosses the galactic plane once 2.4×10^6 years ago at a radial distance of 8.65 kpc. The u and w velocity components are +67 and -283 km/s. The main sequence lifetime of a B1.5V star is of the order of 1.0×10^7 years and since it is normally thought that the components of binary systems form contemporaneously, it seems likely that only for the most massive of companions could the system have evolved to disruption in the time available. With an absolute magnitude of +3 the star is found to have been ejected with u and w velocity components of +134 and -112 km/s.

F 81

This sdB star has an orbit which is not bound and never crosses the galactic plane if an absolute magnitude of +3 is assumed. Using an absolute magnitude of +4 an orbit was found which crossed the galactic plane 1.76×10^8 years ago at a distance of 30.5 kpc from the galactic centre. This seems unlikely and it must be assumed that this star is intrinsically fainter than other sdB stars.

F 91

The orbit of this sdB star crosses the galactic plane twice in the past 5×10^8 years. The latest occasion occurred 23.6×10^6 years ago when r, u and w were 2.1 kpc, +27 km/s and -174 km/s. The previous crossing was 68.8×10^6 years ago when r, u and w were 17.0 kpc, +282 km/s and +57 km/s. There seems to be no reason to prefer either of these alternative times of ejection to the other.

PHL 717

This sdB has no published radial velocity and a range of velocities from -50 to +100 km/s were used. The results are tabulated below,

R.V.	t_0	r_0	u_0	w_0	t_1	r_1	u_1	w_1
-50	37.9	7.46	+165	-165	-	-	-	-
0	28.4	6.48	+70	-146	199	37.5	+138	+30
+50	21.0	6.53	-40	-145	105	23.6	+208	+47
+100	15.6	7.09	-170	-153	103	25.1	+232	+50

The subscripts 0 and 1 refer to separate crossings of the galactic plane. Times are measured in units of 10^6 years, distances in kiloparsecs and the galactic velocity components in kilometers per second. None of the orbits is bound. Clearly the more recent crossings are more likely to be the actual times of ejection.

PHL 197

Again this star has no published radial velocity and values ranging between -50 and +125 km/s were used. The orbits cross the galactic plane only once and the details are tabulated overleaf.

R.V.	t_0	r_0	u_0	w_0
-50	49.8	19.6	+402	-65
0	34.9	14.5	+388	-69
+50	24.4	11.5	+339	-70
+75	20.2	10.5	+299	-72
+100	16.8	9.9	+258	-76
+125	14.0	9.5	+209	-80

Clearly the star has been projected towards the galactic centre at a large velocity. Fig. 7.4 shows the orbits found for radial velocities of -50, 0 and +125 km/s.

From the forgoing results it is clear that a considerable proportion of the B subdwarfs studied have motions which can only be explained by them having been projected with considerable velocity in a direction different from what must previously have been a bound orbit. The simplest explanation for this behaviour would be the sudden disruption of a binary system containing the subdwarf (Blaauw, 1961).

At present the evolutionary status of the sdB stars is in dispute. No evolutionary modelling has been able to substantiate the observational proposal that the sdB stars are part of an extended horizontal branch and related to normal horizontal branch stars. Such phenomena as the Newell gaps (Newell, 1973 and Newell and Graham, 1976) and the observed temperatures and gravities of the stars do suggest that some connection exists. However the production of an sdB star, with a mass of about $0.5M_\odot$, involves substantial mass loss during and after the red giant phase and it

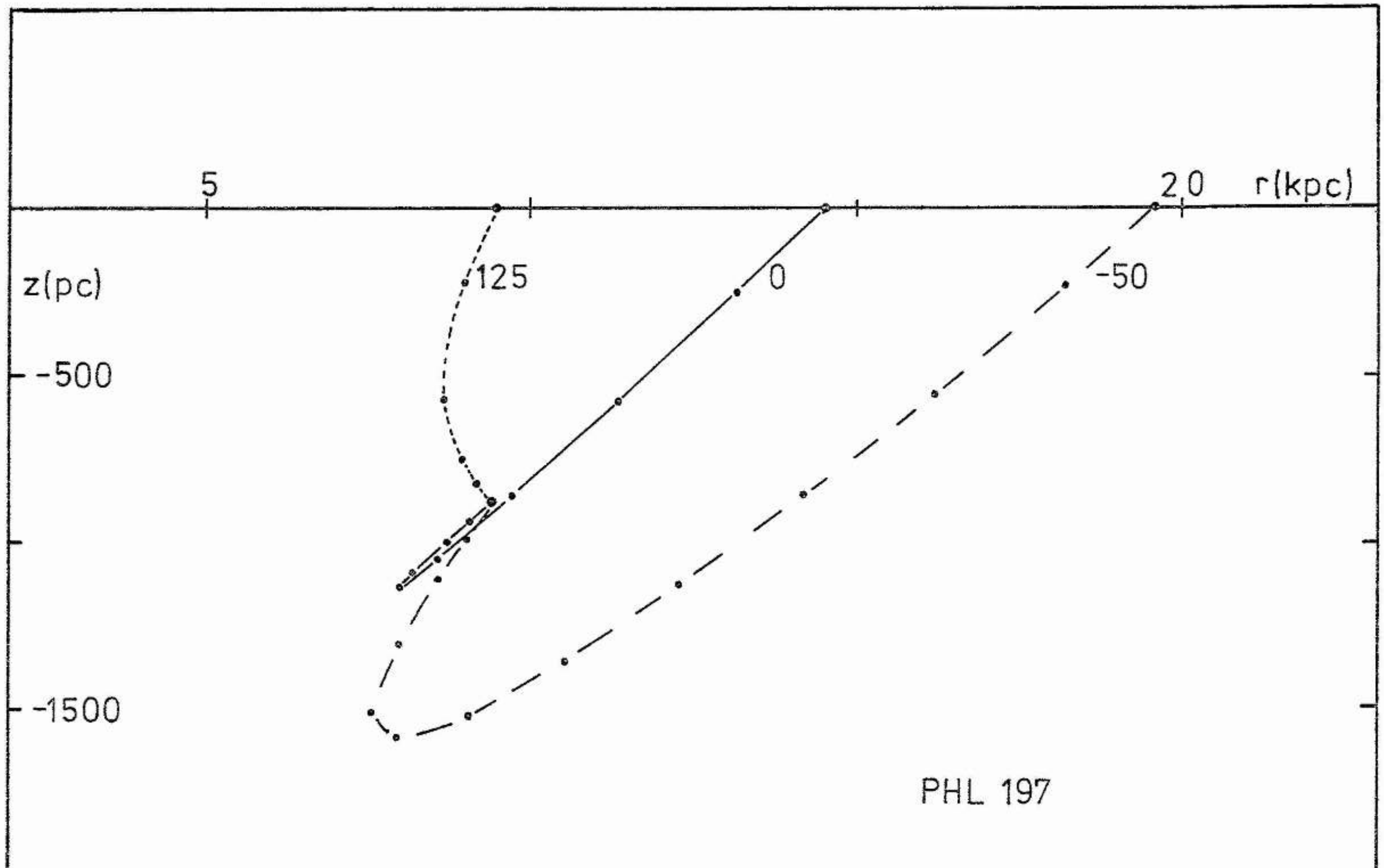


Figure 7.4 The Orbits of PHL 197 for Three Different Radial Velocities

is not clear whether this can be achieved for single stars.

The suggestion that sdB stars form in binary systems (Mengel, Norris and Gross, 1976) has observational support since some sdB stars show radial velocity variations, as outlined by Baschek and Norris (1975). Mengel et al. outlined evolutionary calculations for a binary system which formed an sdB from the primary. However the full evolution of the secondary was not followed and the complete evolutionary behaviour is not clear. It would be convenient if the secondary were to explode, disrupting the system, and producing a high velocity sdB star. This seems unlikely since the total mass of the system is initially $1.58M_{\odot}$ and Mengel et al. suggest that some mass may be lost from the system during rapid mass transfer. Hence the secondary cannot have a mass greater than $1.08M_{\odot}$ and such a star should be able to complete its evolution without any cataclysmic behaviour which might disrupt the system.

Clearly the Mengel, Norris and Gross model does not explain the high velocity sdB stars. It should be noted that this might concern not only those subdwarfs showing unbound orbits but also those, such as PHL 3802, which have highly eccentric orbits and may have been ejected from a system near the galactic centre where the escape velocity is high. Any model of sdB evolution must therefore account for their production in a binary system which may disrupt. At present no other method seems likely to produce the observed motion.

It should be noted that a number of sdO stars also occur in binary systems. Among the brighter sdO stars HD 113001 (Wallerstein and Spinrad, 1960), HD 128220 (Wallerstein and Wollf, 1966) and

HD 49798 (Jaschek and Jaschek, 1963; Thackeray, 1970) are binary while Greenstein and Sargent (1974) found BD-11°162 and F 80 to be systems containing an sdO star. HD 87892 (Kohoutek and Lausten, 1978) and UU Sge (Bond et al., 1978), the central stars of the planetary nebulae NGC 3132 and Abell 63 respectively, are binary with the hot component being an sdO. Bond et al. have suggested that binary systems are involved in the production of planetary nebulae. This process could account for the creation of a large proportion of sdO stars. The planetary nebula quickly dissipates to leave a star which would be indistinguishable from a single sdO, except in special cases such as the eclipsing binaries LB 3459 and UU Sge. There seem to be few very high velocity objects among sdO stars suggesting that if these stars are members of binary systems, the systems are not prone to disruption.

The problems caused by the presence of apparently normal stars at large distances from the galactic plane have been discussed by House and Kilkenny (1978) and Greenstein and Sargent (1974). The situation is basically that either the stars form in the galactic plane and are then ejected or form far from the galactic plane near their present positions. A comparison of the time needed to reach the present position from the galactic plane and the evolutionary lifetime is instructive in deciding between the two alternatives.

Orbits have been calculated for the remaining seven apparently normal stars in Table 7.3 for which proper motions are available. Since no radial velocities are available for these stars, values of -75, 0 and +75 km/s were used to investigate the origins

Table 7.7 Recent Crossings of the Galactic Plane

for Apparently Normal Stars

Star	Spectral Type	R.V.	$t_0(10^6 yr)$	r_0	u_0	w_0	$\tau_{ms}(10^6 yr)$
PHL 159	B1.5	-75	16.6	8.9	-43	-189	10
		0	13.4	9.1	-5	-216	
		+75	11.1	9.3	+32	-257	
PHL 460	B5	-75	-	-	-	-	60
		0	-	-	-	-	
		+75	276	128	+431	-17	
PHL 5382	B7	-75	6.2	4.8	-482	-456	~120
		0	5.4	5.4	-526	-506	
		+75	4.8	5.9	-542	-563	
PHL 375	B7	-75	28.8	8.2	-112	-93	~120
		0	17.4	9.6	-29	-101	
		+75	11.2	9.9	+20	-139	
LB 1502	B9	-75	25.1	1.1	-81	-300	~200
		0	20.1	3.2	-296	-234	
		+75	15.8	5.7	-224	-228	
PHL 1957	B9.5	-75	24.3	8.5	-107	-97	~210
		0	15.0	9.6	-24	-118	
		+75	10.2	9.9	+28	-159	
LB 1652	A0	-75	137	19.2	+99	-154	~220
		0	68	7.4	+176	-271	
		+75	44	2.3	+281	-322	

of these stars. The results are given in Table 7.7 for the first crossing of the galactic plane. Only PHL 460 and PHL 5382 do not have bound orbits. The estimated lifetimes are based on the main sequence lifetimes given by Iben (1967) and are only a rough indication of the time available for the star to reach its present position. Clearly the times available for stars of spectral type B5 and later are large and this type of investigation is better suited to early B stars. If PHL 159 is to reach its present position while still on the main sequence, it must have a radial velocity greater than +75 km/s. The results for PHL 460 are poor and, unless the radial velocity is greater than 150 km/s, it seems unlikely that it is a main sequence star. The other stars have had ample time to reach their present positions. The size of the w velocity component at the supposed time of ejection should be noted as in all cases except PHL 460 it is greater than 100 km/s. This suggests that the binary disruption mechanism is responsible rather than the sling shot process in a multiple system, which gives only small velocities.

This type of investigation is useful in the study of stellar kinematic behaviour and, provided the necessary information is available, places constraints on the interpretation of their evolutionary history. Hence it is important that radial velocities are obtained for many faint apparently normal and subdwarf stars. This would allow a detailed investigation of the evolutionary processes involved. Stars which are not as kinematically peculiar as those studied here must be included to remove the severe selection effects present in the small sample considered. It seems likely that the Blaauw runaway-star process is responsible for the motions of a sizeable number of faint blue stars.

CHAPTER 8

CONCLUSIONS

The work in this thesis has entailed extensive observing but the part relating to the new photometric systems can still only be considered as preliminary. It is now useful to consider what has been achieved and what future developments are desirable.

The Strömgren photometry described in Chapter 3 completes the faint blue star survey for stars brighter than 12^m in the southern hemisphere. Although the photometric survey is only partially complete, it is interesting to consider the distribution of stars in type and magnitude. Histograms for various classes of star are shown in Fig. 8.1. The faint blue stars from Chapter 3 are hatched to the right while the TD-1 Survey stars are hatched to the left. The other stars are from the photometry papers listed on page 136. The distributions are truncated at brighter magnitudes by the selection of the stars and at the fainter by the present incompleteness of the survey. However it is clear that among the stars of 12^m and 13^m the proportion of main-sequence stars is declining while the proportion of hot subdwarfs is increasing. In the case of the horizontal branch stars the peak of the distribution is probably near $13\overset{m}{.}0$ but this will only be known for certain when the survey is more complete. The range of magnitudes considered is still too bright for white dwarfs to be found in large numbers.

Undoubtedly Strömgren photometry is generally successful for classification, the major problem being among the possibly

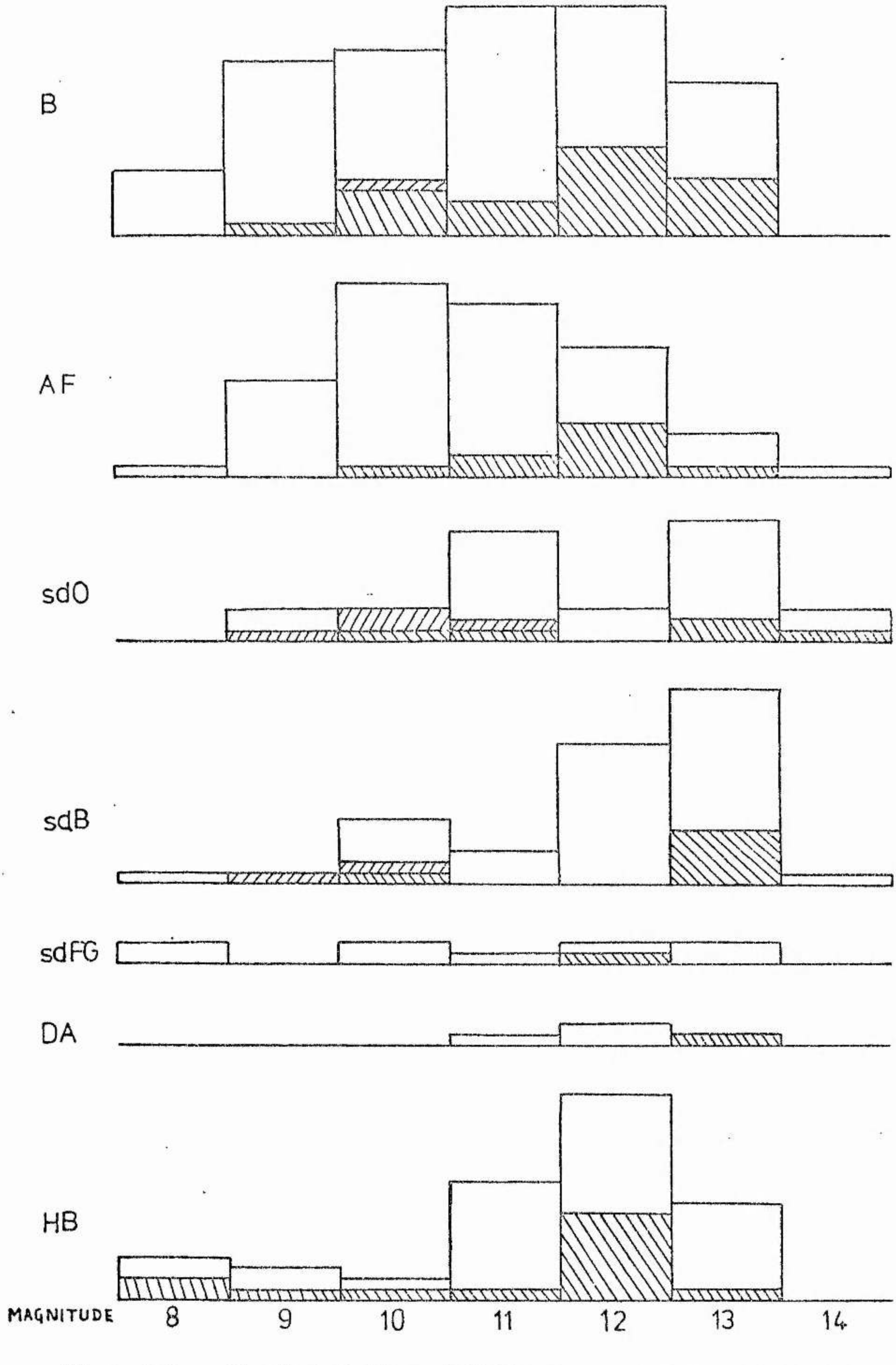


Figure 8.1 The Distribution of Stellar Types at Different Magnitudes

(Vertical scale is 0.2 cm per star)

subluminous B stars which cause difficulties whatever method of investigation is used. The Strömgren index [u-b] has been found to provide a good temperature indicator when the calibration of Davis and Shobbrook (1977) is used. The calibration of Osmer and Peterson (1974) is also useful when stars with small amounts of reddening are studied and the calibration of Philip and Newell (1975) can also be used provided θ is less than 0.35.

The 38 photometry system, although undoubtedly needing many more observations before becoming firmly established, has proved to be very useful. It allows more certainty of classification, especially for the hot subdwarfs with their very negative (u-38) values and for reddened stars near A0 where the c_1 index passes through its maximum. However the most striking feature of the 38 photometry is the linear relationship between [38-b] and the Hβ index. This relationship will be more definite when reddening ratios for the 38 filter are determined observationally from a study of reddened O stars. [38-b] forms the basis of a powerful technique for the determination of B star absolute magnitudes and the advantage of using an intermediate filter rather than Hβ filters is considerable. It should be possible to study all the stars on the St. Andrews faint blue star programme with the 38 filter while this would require a very large telescope if Hβ photometry was to be used.

The results with the 4686 filters are satisfying in that the 4686 index gives a method of identifying DO, sdO and O stars without any assumptions about the presence of interstellar reddening. The index is well correlated with the equivalent width of the HeII λ4686 line and this property lends itself to studies of line variability in Of stars or line changes due to binary orbits for which a good candidate would be 29 CMa. The behaviour of the index with absolute magnitude has shown the work of Landolt (1970) to have been better than previously thought but the use of a linear fit between the two parameters is an oversimplification which does not take account of differences in behaviour between luminosity classes. The determination of absolute magnitudes from the indices of dwarfs and giants is difficult without a knowledge of the spectral type. Since an absolute magnitude could be estimated from the spectral type itself, the argument for the use of 4686 filters for this purpose is considerably weakened. Certainly more northern stars with accurate absolute magnitudes should be studied to clarify the 4686 index - M_V relationship before it can be used seriously for absolute magnitude determination.

The investigation of image tube spectra has shown that in general 30A/mm spectra are suitable for use with the Greenstein and Sargent (1974) method of determination for surface gravity from Balmer line widths. In addition radial velocities of reasonable quality are obtainable from these spectra. It would be useful if the stability of the S.A.A.O. Image Tube Spectrograph was better established by an extensive study of radial velocity standard stars over a range of hour angle, declination and temperature but this would be more appropriately done by the staff of S.A.A.O. Further observations of the O and B subdwarfs would be valuable in checking the suggestion that all these stars are binary. From the results in Chapter 6 it seems possible that at least F 66, HZ 44 and GD 298 might show velocity variability. The use of 75 A/mm spectra is preferable for spectral classification since a larger spectral range can be studied including the Balmer discontinuity.

The number of faint apparently normal main-sequence stars known to exist in the halo is increasing due to surveys such as the St. Andrews faint blue star programme. This causes problems for theories which account for the presence of such stars. The number of stars involved seems too large for the Blaauw (1961) binary-disruption mechanism to be responsible for them all. Also the proposal by Greenstein and Sargent (1974) that two kinematic groups are present suggests the action of more than one mechanism. Even though it can be shown that most of these stars may be formed in the galactic plane and reach their present positions within their evolutionary lifetimes, the more important question is why they should do this. It would be very interesting to study a few of these stars with high dispersion spectra. This could be done using the Anglo-Australian Telescope. It should then be possible to decide whether the stars are subluminous or dwarfs with normal abundances. This same equipment would also be useful for the study of sdO and sdB stars at high dispersion. Both the normal stars and the subdwarfs could profitably be studied in the ultraviolet by the International Ultraviolet Explorer satellite. Abundance analyses for the subdwarfs are very desirable in the context of their evolutionary position. This is more feasible since the necessary model atmosphere techniques are now available for such work.

It has been shown in this thesis that, although Strömgren photometry provides reasonable classifications for most faint blue stars, the new filter systems described can provide valuable additional information. However the new systems need more work before they are fully established. By the use of both spectroscopy and photometry it is possible to obtain values for the physical properties of faint blue stars, which lead to a better understanding of these stars.

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